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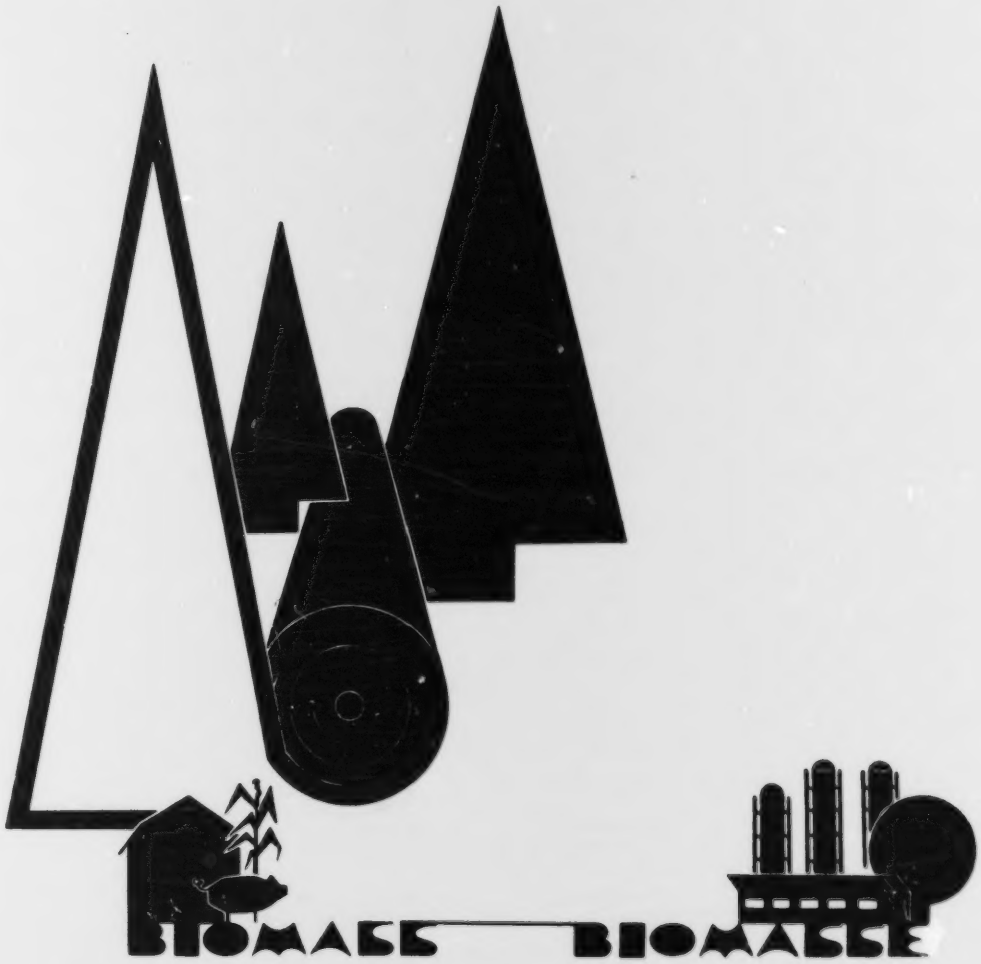
Analysis of Short Rotation Forest Operations

Theodore B. Golob

June 1986



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ANALYSIS OF SHORT ROTATION FOREST OPERATIONS

Theodore B. Golob

Bioenergy Program, Division of Energy
National Research Council of Canada
Ottawa, Canada

June 1986

TABLE OF CONTENTS

	Page
SUMMARY	ix
RÉSUMÉ	x
INTRODUCTION	1
OPERATIONS ANALYSIS	5
BIOLOGICAL FACTORS	5
Species and Clones	5
Yield	5
Fertilization	7
Plantation Sites	8
LAND PREPARATION	9
Brush	9
Root Removal	9
Plowing, Disking, and Harrowing	11
Application of Chemicals	11
NURSERY OPERATIONS	11
Production of Whips	11
Production, Handling, and Storage of Cuttings	13
PLANTING OPERATIONS	13
Handling of Cuttings and Planting	13
TENDING OPERATIONS	15
Chemical Weed Control	15
Mechanical Weed Control	15
HARVESTING OPERATIONS	15
Small Dense Growth	16
Small Single Trees	16
Large Single Trees	17
Coppice Growth	20
CHIPPING AND TRANSPORTATION OPERATIONS	20
Chipping	20
Transportation System	22
COST AND PRODUCTIVITY	23
COMPUTATIONS	23
Capital Cost	23
Interest Rates	24
Equipment	25
Insurance and Shelter	26
Labour and Overhead	26
Energy	26
Equipment Repair	27

TABLE OF CONTENTS (Cont'd)

	Page
Service and Supplies	27
Total Operational Costs	27
LAND PREPARATION - COST AND PRODUCTIVITY	28
Brush Removal	30
Stumps and Stones	31
Plowing and Disking	31
Harrowing and Chemicals	31
Total Cost of Land Preparations	32
NURSERY OPERATIONS - COST AND PRODUCTIVITY	33
Harvesting of Whips	34
Production, Handling and Storage of Cuttings	36
PLANTING OPERATION - COST AND PRODUCTIVITY	40
Handling and Transportation of Magazines	41
Planting	43
Total Cost of Planting Operations	43
TENDING OPERATIONS - COST AND PRODUCTIVITY	45
Mechanical Weed Control	46
Chemical Weed Control	46
HARVESTING - COST AND PRODUCTIVITY	49
Harvesting Small Dense Growth	49
Harvesting Small Single Trees	54
Harvesting Large Single Trees	57
Harvesting Coppice	58
CHIPPING - COST AND PRODUCTIVITY	59
Productivity	59
Cost	60
TRANSPORTATION - COST AND PRODUCTIVITY	60
Productivity	62
Cost	63
EQUIPMENT TRANSPORTATION - COST AND PRODUCTIVITY	63
Productivity	65
Cost	66
COST PER OVEN DRY TONNE	66
Cost of Land Operations per Oven Dry Tonne	68
Cost of Nursery Operations per Oven Dry Tonne	70
Cost of Planting Operation per Oven Dry Tonne	74
Cost of Tending Operation per Oven Dry Tonne	74
Cost of Harvesting Operation per Oven Dry Tonne	75
Cost of Chipping Operation per Oven Dry Tonne	76
Cost of Chip Transportation per Oven Dry Tonne	76

TABLE OF CONTENTS (Cont'd)

	Page
TOTAL COST PER OVEN DRY TONNE FOR ALL OPERATIONS	77
Cost per Oven Dry Tonne for 5-Year Rotation Plantations	77
Cost per Oven Dry Tonne for 10-Year Rotation Plantations	79
Cost per Oven Dry Tonne for 2-Year Rotation Plantations	80
MACHINE DEVELOPMENT	83
TERRAIN-VEHICLE-SYSTEMS DEVELOPMENT	83
MACHINES FOR LAND PREPARATION	84
Brush Harvester	84
Root Cutter-Collector	85
MACHINES FOR NURSERY OPERATIONS	87
Whip Harvesting Machines	87
Machines for Production of Cuttings	92
MACHINES FOR PLANTING OPERATIONS	95
Automatic Planter for Cuttings	96
Transportation Vehicles for Magazines	99
TENDING MACHINES	99
Equipment for Mechanical Cultivation	99
Equipment for Application of Fertilizers	99
Applicators of Chemicals	101
HARVESTING MACHINES	101
Small Single Tree Harvester	102
Large Single Tree Harvesters	108
Small Dense Growth Harvester	110
Large Growth Coppice Harvester	112
CHIPPING EQUIPMENT	116
Transportation Equipment	119
CONCLUSIONS	121
ACKNOWLEDGEMENTS	123
REFERENCES	123

LIST OF FIGURES

1	Fully mechanized SRF operations	2
2	Land preparation operations	10
3	Fully mechanized SRF nursery operations	12
4	SRF planting and tending operations	14
5	SRF harvesting operations - 4-row harvester	18
6	SRF harvesting of large trees - 2-row harvester	19
7	Roadside chipping and transport operations	21
8	Productivity analysis of a land preparation operation system	29

LIST OF FIGURES (Cont'd)

		Page
9	Analysis of land preparation costs	33
10	The productivity analysis of a single row whip harvester	35
11	The analysis of whip harvesting costs	37
12	Productivity of an automatic system for production and storage of cuttings	38
13	The cost analysis of the production of cuttings	40
14	Analysis of planting productivity for a 5-year rotation plantation	42
15	Analysis of planting costs for a 4-row planting system	43
16	Analysis of planting costs for a 6-row planting system	44
17	Analysis of the tending productivity for a 5-year rotation plantation	47
18	Cost analysis of the tending operation in a 5-year rotation plantation	48
19	Productivity analysis of the 4-row harvesting operation in a 2-year rotaion plantation	52
20	Analysis of 4-row harvesting costs for a 2-year rotation plantation	53
21	Analysis of the 4-row harvesting productivity in a 5-year rotation plantation	55
22	Analysis of harvesting costs for a 4-row harvesting system in a 5-year rotation plantation	56
23	Analysis of the productivity of a 2-row harvesting system in a 10-year rotation plantation	58
24	Cost analysis of the 2-row harvesting system in a 10-year rotation hybrid poplar plantation	59
25	Analysis of chipping productivity	61
26	Cost analysis of the chipping operation	62
27	Analysis of the chip transport productivity for 6.5 productive hours out of an 8 h shift	64
28	Analysis of chip transportation costs	65
29	Analysis of the equipment transportation costs	67
30	Cost/ODt for 5-year rotation plantation with a yield of 50 ODt/ha	78
31	Cost/ODt for 5-year rotation plantation with a yield of 60 ODt/ha	78
32	Cost/ODt for 10-year rotation plantation with a yield of 62 ODt/ha	79
33	High cost/ODt for 10-year rotation plntation with a yield of 62 ODt/ha	80

LIST OF FIGURES (Cont'd)

		Page
34	Cost/ODt for 2-year rotation plantations with a yield of 20 ODt/ha	81
35	Cost/Odt for 2-year rotation plantations with a yield of 24 ODt/ha	82
36	Brush harvester	86
37	Root cutter-collector	88
38	NRCC whip harvester	90
39	Band saw severing device for whips	91
40	Automated production of cuttings	93
41	Details of NRCC automatic planter	98
42	Loading of magazines on planter	100
43	NRCC prototype harvester for 5-year rotation plantations	103
44	Infeed and severing devices on the 5-year rotation harvester	105
45	Device (a) for unloading bunches parallel to the travel, device (b) unloading at right angle to the travel	106
46	Front end piler gathering bunches of trees	107
47	Concept of a 4-row harvester for 5-year rotation plantations	109
48	Concept of a 2-row harvester for 10-year rotation plantations	111
49	Coppice harvester for large coppice growth	113
50	(a) Saw pitch configuration; (b) Power requirements	115
51	Roadside landing biomass chipping system	117
52	A typical unloading system at the plant	118

SUMMARY

This analysis studied short rotation forest (SRF) operations with the goal of establishing the optimum level of mechanization of SRF operations related to the 1985 cost of wood chips delivered to pulp mills, and to the cost of heating oil based on relative heating values of wood and oil.

The SRF rotation periods and their respective harvest yields per hectare and costs per oven dry tonne of wood chips were analysed. The medium 5-year rotation (at $31.76/ODt) and long 10-year rotation plantations (at $30.78/ODt) are more economical then the short 2-year rotation plantations (at $56.47/ODt), because of a relatively low harvest yield per hectare of 2-year rotation plantations.

The cost of heating oil of an equivalent heating value of a tonne of oven dry wood chips is $139.00 for industrial users at the price of $0.35 per litre of oil, and $178.00 for home users based on the price of $0.45 per litre of oil.

The 1985 low price per tonne of oven dry wood chips delivered to pulp mills is $49.00. All costs and prices are expressed in 1985 Canadian dollars.

The biomass grown in SRF plantations is competitive on the open market with prices of wood fiber used in pulp mills, and with the price of oil used in direct combustion.

The SRF plantations are normally planted on low grade abandoned agricultural land, thus potentially providing a cash crop in most depressed farm areas.

RÉSUMÉ

La présente évaluation de la méthode de sylviculture à rotation rapide (SRR) à l'étude au CNRC vise à établir la longueur optimale du cycle de rotation en comparant le coût de production de la SRR avec le prix actuel de copeaux de scierie livrés à l'usine de pâte et avec le prix des huiles à chauffage résidentiel et industriel.

Le rendement de la SRR est étudié en déterminant la productivité, exprimée en tonne séchée au four par hectare, pour trois periods de rotation. Les rotations à moyen et long termes offrent des productivités (50 tsf/ha sur 5 ans et 62 tsf/ha sur 10 ans) plus rentable que celle d'une rotation à court terme de 2 ans (20 tsf/ha), essentiellement parce que les deux premières années de croissance produisent beaucoup moins de bois récoltable.

Le coût de production de copeaux de sylviculture, exprimé en dollars canadiens de 1985 par tsf livrée à l'usine, varie d'aussi peu que de 32 à 31 $/tsf pour des cycles de 5 à 10 a, mais s'élève à 56 $/tsf pour 2 a.

Au prix actuel de 35¢/L, le coût d'une quantité d'huile à chauffage industriel de pouvoir calorifique équivalent à une tonne de copeaux est de 139 $/tsf, et il est de 178 $/tsf pour de l'huile à chauffage résidentiel à 45 ¢/L. Le prix, actuellement bas, des cipeaux de scierie est de 49 $/tsf livrée à l'usine.

Le coût de la biomasse produite par SRR apparaît concurrentiel avec les cours actuels sur le marché des copeaux de scierie, et de beaucoup meilleur marché que l'huile industrielle.

Les forêts à sylviculture courte serait plantées dans des terres agricoles abandonnées de basse qualité, ce qui ouvre une nouvelle source de revenu aux populations des régions agricoles économiquement rallenties.

ANALYSIS OF SHORT ROTATION FOREST OPERATIONS

T.B. Golob

INTRODUCTION

Forests are being depleted at a very fast pace throughout the world; the lack of an adequate supply of wood will affect the well-being of people in many ways. As the forest cover is stripped away, the climatic conditions change because of the interrupted cycle of the retention and release of water and with it nutrients.

Some reports claim that only a fraction of the existing forest land capable of high yields could meet world demand for wood (Sedjo, 1983). Industrial forest plantations designed to optimize operational and economic factors are gradually replacing humanity's reliance on old-growth forests.

Short rotation forestry (SRF) brings a new concept in managing forest crops by applying techniques developed for agricultural row crops. Because of the intensive nature of the management of short rotation forests, it is very important to develop fully mechanized operational systems. The supply of biomass from SRF plantations depends on the economics of the overall supply systems. An example of a fully mechanized system of short rotation forest operations is illustrated in Fig. 1. All operational systems reflect the intensive agricultural nature of the optimized machine systems, designed for the most economic productivity, based on potential biomass yields.

The analysis of SRF operations requires the study of many factors that can be identified with the execution of certain stages of industrial work leading to production of wood through intensive management of plantations. This is an engineering analysis of operations, costs, and mechanical systems; as such, the study is based on an industrial engineering approach to the analysis of systems and costs, where all inputs are segregated and presented in the simplest possible aggregate format. The costs are treated in a manner compatible with economic and financial analysis practices. In this analysis all operational and biological factors are considered from the viewpoint of the mechanical engineering machine designers. To develop a harvesting machine the designer requires information on the plantation layout, the spacing of trees, and on the access road; also, the tree sizes needed to design the machine must be given in terms the designer can use. The diameter at breast height (DBH) is of no value to the designers of harvesting equipment. To design the cutting head for a machine one must know the tree stump diameters. Also, to design tree handling equipment it is important to know the statistical distribution of the weight and the

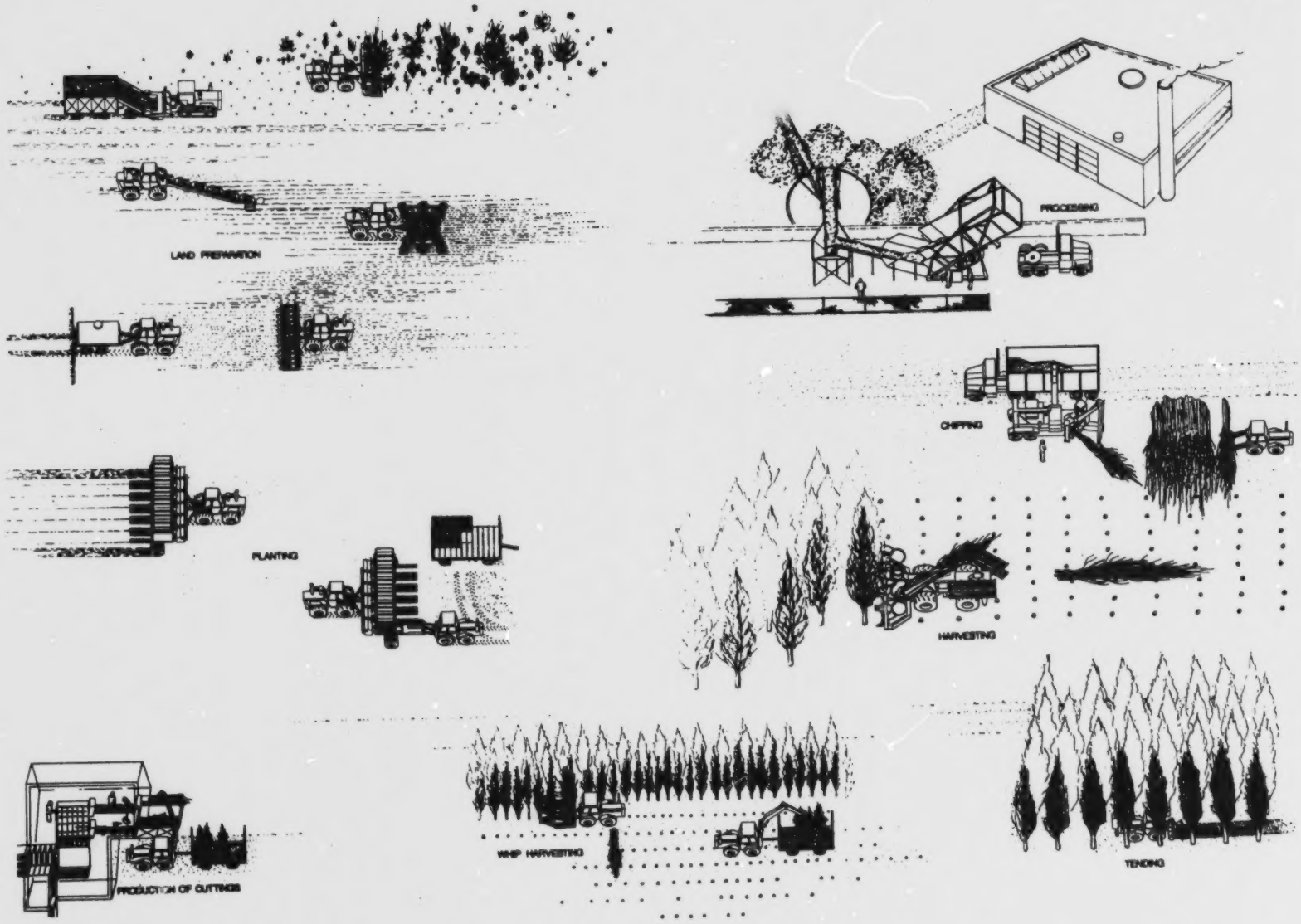

Figure 1. Fully mechanized SRF operations

height of trees for a given rotation and species. The upper and lower deviation from the mean of the tree weights and of their stump diameters must be given in good statistical terms. Without this statistical information the designer must approximate the stump diameter from the available DBH figures. Also, to obtain the average weight of trees one must convert the information on the yield per hectare to the average weight of trees by applying a known rate of the tree survival, thus arriving at the number of trees per hectare for the given yield.

The wood taken out of forests is valued by its use and by the distance to the point of use, pulp mill, lumber mill, or veneer mill. In most regions in Canada and the United States the base value of standing wood is given in terms of stumpage dues. The stumpage is the cost of wood to the contractor who is supplying the wood to the mill; often, this cost does not reflect the true replacement value of the standing timber. The costs of clearing the land, scarifying, planting, and the cost of planting stock are not necessarily reflected in the stumpage dues. The minimum 1985/86 season stumpage crown dues for spruce in Ontario are $3.72 per green tonne[1] or, at a moisture content of 50% green base, it is $7.44 per oven dry tonne. The timber replacement cost is estimated to be at least double the stumpage cost, assuming well-mechanized regeneration operations; otherwise the costs would be considerably higher.

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[1] Marcus, E. 1985. Crown Dues - 1985/86 Season. Ministry of Natural Resources, Toronto, Ontario. Internal document file: 740-2.

OPERATIONS ANALYSIS

BIOLOGICAL FACTORS

The most important fast-growing trees presently considered for short rotation forest plantations are poplars *(Populus spp.)* and willows *(Salix spp.)*. Research on willow plantations is reported from Sweden (Siren, 1985) and Newfoundland (Dyer, 1983). Work in the development of poplar plantations is more advanced with experimental and production plantations established in many areas of North America. The hybrid poplar program in the Eastern Ontario Region of the Ministry of Natural Resources is one of the most developed SRF programs; the program is described as that of "farming fast growing hardwoods" (Anon, 1980). The short rotation forests are also referred to as agro-forestry, where the fast-growing hardwoods are treated as an agricultural crop.

Species and Clones

The native Canadian poplars: trembling aspen *(Populus tremuloides Michx.)*, largetooth aspen *(Populus grandidentata Michx.)*, balsam p *(Populus balsamifera L.)*, eastern cottonwood *(Populus deltoides Ba* black cottonwood *(Populus tricocarpa Torr. & Gray)*, and narrowleaf co wood *(Populus angustifolia James)* are fast-growing short-lived trees shed leaves each autumn; they are supported by wide-spreading shallow root systems and propagate chiefly by means of suckers from the roots and stumps (Hosie, 1969). The most promising specimen of the native species are crossed with poplar species from the United States and Europe. Superior progeny are then used in further breeding of the most desirable clones (Anon, 1983). There are more then 150 clones in production in the Eastern Ontario Region, including some more recent aspen and balsam hybrids (Barkley, 1983).

Yield

Spacing and rotation are interdependent; there is an optimum harvest rotation for a given spacing of trees in a plantation. The yield of the plantation depends on the clone, soil, spacing of trees, tending practices, fertilization, climatic conditions, and the number of growing seasons. The present thinking on the number of years to harvest divides plantations into three general categories: short, medium, and long rotations of, respectively, 2-3, 5-7, and 8-12 years. The short rotation has a spacing of approximately 1 m between rows and 0.3 m between trees. This spacing gives stocking density of around 0.33 trees/m^2. The medium rotation plantations have a spacing between rows of around 1.5 m and between trees of 1.5 m and can be considered as an intermediate plantation of relatively small trees; area per tree is around 2.25 m^2. The long rotation plantation with a

spacing of about 3 m between trees and 3 m between rows of trees will produce large trees in rotation periods from 8 to 12 years, with an area of around 9 m^2 per tree. The rotations between harvests for all three categories of plantations are not necessarily fixed to a rigid number of years because of possible variation in the yearly productivity due to biological and climatic conditions. However, in a large scale operation where the output is related to a fixed biomass requirement, rotation periods may be fixed if the variation in the annual yield per hectare can be compensated by the reserve plantation area that can be allocated if needed to maintain a required production.

The yield is normally reported in green tonnes per hectare or in oven dry tonnes per hectare; also in some reports it is stated in tonnes of dry matter with an assumed moisture content of 55% dry basis (Pohjonen, 1984), or approximately 26% wet basis. When referring to oven dry tonnes (ODt) the moisture content is assumed at 8% wet basis, while the green wood is assumed at a moisture content of 50% wet basis, and seasoned dry wood is assumed at a moisture content of 20% wet basis (Love and Overend, 1978). Since there is little information on yields of various species under all combinations of all possible variables it is difficult to analyse the economic aspects of SRF plantations without making assumptions on potential yields at various tree spacings and rotations. The optimal densities of trees per square metre and their projected yields vary greatly. Reported densities of one tree per 0.05 to 0.37 m^2 were necessary for annual biomass yields of 15 to 20 ODt from first rotation fertilized and irrigated hybrid poplar plantations (Strauss et al., 1984). An estimated mean annual increment of 16 ODt/(ha a) (ODt/(ha a) = oven dry tonnes per hectare per year) is reported as feasible, with a better developed biomass production technology (Anon, 1983). This would give a yield of 32 ODt/ha in a 2-year rotation plantation. The best results reported for a 2-year rotation willow plantation are 3.5 to 3.9 kg of dry matter per square metre, or 35 to 39 t of dry matter per hectare for a 2-year rotation, and about 60 t of dry matter for a 3-year rotation intensive energy plantation (Siren, 1985). Taking dry matter at 20% moisture content wet basis, if converted to oven dry wood at 8% moisture content the yield becomes 30 to 34 ODt/ha for a 2-year rotation plantation, and 52 ODt/ha for a 3-year rotation intensive energy plantation. A practical expected yield for a 2-year rotation hybrid poplar plantation that was not fertilized or irrigated is perhaps 18 to 20 ODt/ha per harvest; at 85% survival the standing plants would weigh an average of 1.27 to 1.41 kg, assuming a plantation spacing of 1 m between rows and 0.3 m between plants. The present reported figures indicate a possible 100% increase in the yield by fertilizer and irrigation treatment of 2-year rotation plantations.

There is less published information on 5-year rotation poplar plantations. A yield of 8.35 ODt/(ha a) (Anon, 1983), and 10 ODt/(ha a) (Anon,

1980) for 42 and 50 ODt per harvest, or 22 and 26.5 kg per tree at 85% survival is projected for Eastern Ontario 5-year rotation hybrid poplar plantations. This projection could probably be substantially increased by improved treatment of plantations. Some statistics indicate that an average 5-year rotation hybrid poplar tree weighs 32 kg (Barkley, 1985). If the spacing of trees is 1.5 m between trees and 1.5 m between the rows of trees, and if the survival is 85%, then at an average of 32 kg per tree the plantation would yield 60 ODt/ha of biomass per rotation; for a mean annual increment of 12 ODt/ha. The reports indicate that 42 to 50 ODt per harvest can be assumed as low and high yield limits for the present 5-year rotation hybrid poplar plantations in Eastern Ontario, giving average standing tree weights of 22 to 27 kg at 85% survival.

The 10-year rotation plantations are referred to as low density, moderately high yielding, fibre production plantations with an average annual increment of 6.4 ODt (Anon, 1980). The spacing of trees is 3 m by 3 m which, at 85% survival makes for 944 trees per hectare; 6.4 ODt/(ha a) makes 64 ODt at the harvest in 10 years, or 128 t of green wood which is approximately 136 kg per tree. A reported 10-year-old poplar plantation with a spacing of trees at 3.6 m by 3.6 m yielded 44 ODt.[1] The survival was 77% and the average tree weighed 149 kg. This plantation was one of the earliest experiments in poplar plantations in eastern Ontario. The available weights for 10-year-old poplar trees, of 136 and 149 kg and 64 and 44 ODt/ha are not considered sufficiently reliable for the analytical purposes; however, the figures are the only indication of a possible productivity of 10-year rotation hybrid poplar plantations.

The biological research and trials are extensive; there is a need for better knowledge in the areas of clone to site correlation, resistance of various clones to pests and disease, the optimum combination of spacing, rotation, and yield (Anon, 1983a; 1983b; Barkley, 1983). Most projections of yields for various combinations of the many variable inputs are tentative.

Fertilization

Fertilization, irrigation, and yield trials are in their initial stages (Anon, 1983), with some reports indicating a 56% to 91% increase in yield by applying fertilizer to plantations (Strauss et al., 1984). Trials with sewage sludge are reported to increase yield in hybrid poplar plantations (Riha, Senesac, and Naylor, 1984). The mixed poplar and alder *(Alnus rubra)* plantations indicate that poplar in pure stands renders better yield than in mixed plantations; however, the nitrogen fixing activity by the alder in the first and second years proved beneficial to the growth of

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[1]Barkley, B.A. 1985. Private communication.

poplars (Heilman and Stettler, 1983). Dual cropping and mixed poplar-alder trials indicate a possible economic advantage in growing agricultural cash crops between the rows of poplar plantations until the trees reduce the sunlight to the cash crop.

Biological productivity is of a decisive influence on the success or failure of SRF operations. It is affected not only by the clone, but also by many climatic atmospheric and pedological influences.

Plantation Sites

Researchers agree on the importance of matching hybrid clones to the specific plantation site (Anon, 1980; Anon, 1983; Barkley, 1983; Siren, 1985). However, Siren (1985) claims that it is easier to list soils that are not suitable than to select suitable soils from biological and technical points of view. The difficulty in matching clones to soil sites depends on the general approach to SRF plantations. Biomass plantations can be established either to establish new industry on marginal land or to provide an alternative cash crop. In Eastern Ontario the main effort is in reclaiming abandoned agricultural land (Anon, 1980; Anon, 1983a, 1983b; Barkley, 1983). This land is considered marginal or submarginal for growing agricultural crops; a variety of very poor soil types must be matched to hybrid clones that would produce economically acceptable yields. The trials show that a good clone-to-soil type match will produce trees of vigorous growth with a very high rate of survival, as opposed to poor growth and a low rate of survival (Anon, 1983). Some economic studies compare SRF plantations to other agricultural cash crops (Strauss et al., 1984). The land in these trials was good, productive agricultural land.

In Eastern Ontario clone-site trials poplar plantations may have up to 20 clones planted in a random pattern of 2 ha blocks. These clones were chosen on the bases of previous clone-site trials (Anon, 1980). Approximately 100 clone-site trials have been established in Eastern Ontario since 1976 (Anon, 1983). A soil survey prior to the establishment of a plantation will determine soil characteristics that will indicate which clones should be considered for any given variation of soil texture, depth, moisture, and acidity. Barkley (1983) separates hybrid poplar into three groups, each having somewhat similar site requirements: the cottonwood-type, aspen-type, and balsam-type hybrids.

The cottonwood-type hybrids require a lot of water and good soil aeration. Loams and silt loams can be considered good sites. The pH values should be 7.0 or higher. The aspen-type hybrids prefer drier sites; sandy loam and loamy sand with pH ratings of less then 7.0 are considered best. The balsam-type hybrids are more tolerant of extreme soil conditions; the best growth is associated with imperfectly drained, fine-textured soils (Barkley, 1983).

LAND PREPARATION

The preparation of land for the establishment of SRF plantations involves several operations, depending on the state of the land proposed for the plantation site. In the case of abandoned agricultural land the preparation will involve the removal of brush, roots, stumps, and stones, followed by plowing, disking and harrowing, and the application of chemicals.

A typical agricultural operational system designed for the SRF land preparation is illustrated in Fig. 2. On established agricultural land only the last four operations illustrated are required.

Brush

The removal of brush can be done in a number of ways, depending on the available equipment and whether or not the brush biomass should be harvested and used as a source of energy.

The most common method in the past was to bulldoze the brush, including roots, and pile it on the perimeters of the field. In some cases the brush is cut and chopped with heavy disks (Anon, 1970). Also, there are several front-mounted attachments for tracked and wheeled carrier vehicles, designed to cut and mulch the brush in front of the moving vehicle (McKenzie and Miller, 1978). Dedicated, self-propelled machines have been designed to cut and chip the brush in one operation (Koch and Savage, 1980; Pallari, 1976; Curtin and Barnett, 1985; Elms, 1984). These machines are large and slow, requiring high power input. Collection, storage, and transfer of chips can be a problem. The brush harvesting machine illustrated in Fig. 2 is being developed by the NRCC.[1] This attachment to a medium-sized farm tractor will cut and collect brush biomass. The sale of this biomass will partly compensate for the expenses incurred in the land preparation operation.

Root Removal

There are several attachments for tracked vehicles that undercut the roots of trees and bring these roots to the surface. Also, equipment exists for collecting stones on the ground surface and loading them on field wagons. The root and stone removal operation illustrated in Fig. 2 would cut, collect, and remove stumps, roots, and stones in one operation.

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[1] Hamilton, D.D. 1985. Development of a brush harvester. Logging Development Corporation, Montreal, Quebec. NRCC Int. Rep Contr. No. OSR84-00129.

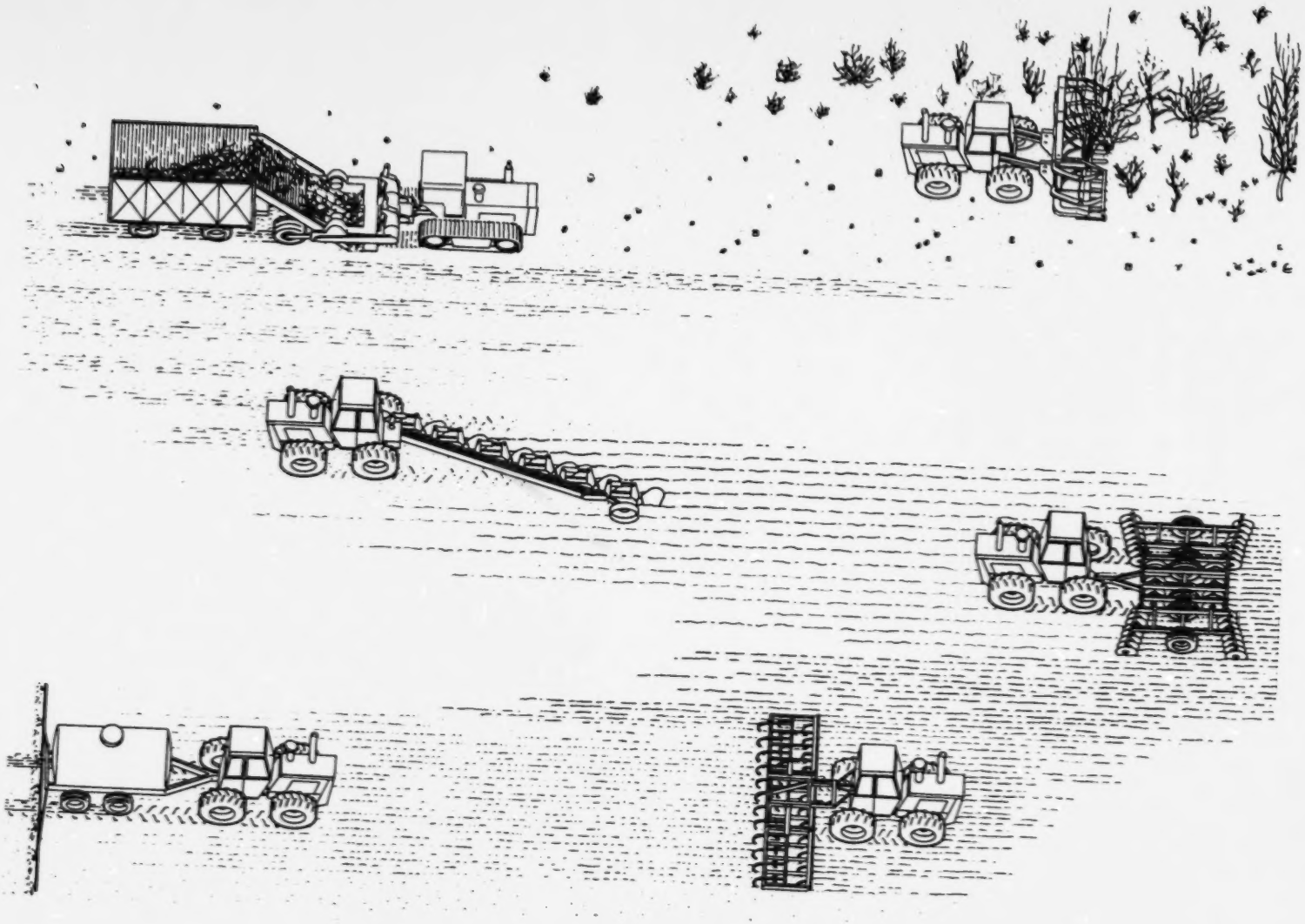

Figure 2. Land preparation operations

Plowing, Disking, and Harrowing

The operations of plowing, disking, and harrowing are normal agricultural operations needed to prepare a site for planting, once the roots, stumps, and stones have been removed. The only exception to the usual agricultural practice is the plowing, which calls for 25 cm depth to accommodate 25 cm cuttings.

Application of Chemicals

Included in the application of chemicals are weed and pest control chemicals, as well as fertilizers. In this study these operations are normally addressed within the tending operation; however, application of weed control chemicals before a planting operation is usually done parallel to the harrowing or just after it. The equipment for the application of chemicals before planting are commonly used sprayers.

NURSERY OPERATIONS

The two nursery operations, production and harvesting of whips and the production of cuttings, are illustrated in Fig. 3. These operations are fully mechanized systems under study and development by the NRCC.

Production of Whips

Production of whips for cuttings involves the establishment of the whip plantation, with a 30-cm spacing of plants within rows and row spacing of 1 m. The number of cuttings needed to establish a whip plantation is more then 33 000 per hectare; at present the harvesting of whips is done by hand, a very slow and labour intensive operation, which, due to the numbers, makes it a very costly operation. Once cut, the whips are bundled, loaded on field wagons, and taken to the plant for the production of cuttings. The whip harvesting illustrated in Fig. 3 cuts and bundles whips in a continuous operation.[1] This harvester is under development by the NRCC. The present plans are for six rotations before replanting. In the second and subsequent rotations there are on the average four whips per stool. The butt diameter of whips varies between 1 and 4 cm. The length of whips varies between 2 and 3 m.

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[1] Jasinski, S.K., and Sulima, S.C. 1985. Development of a whip harvester for hybrid poplar cuttings. HYD-MECH. Forestry Ltd., Woodstock, Ontario. NRCC Int. Rep. Contr. No. OSX83-00104.

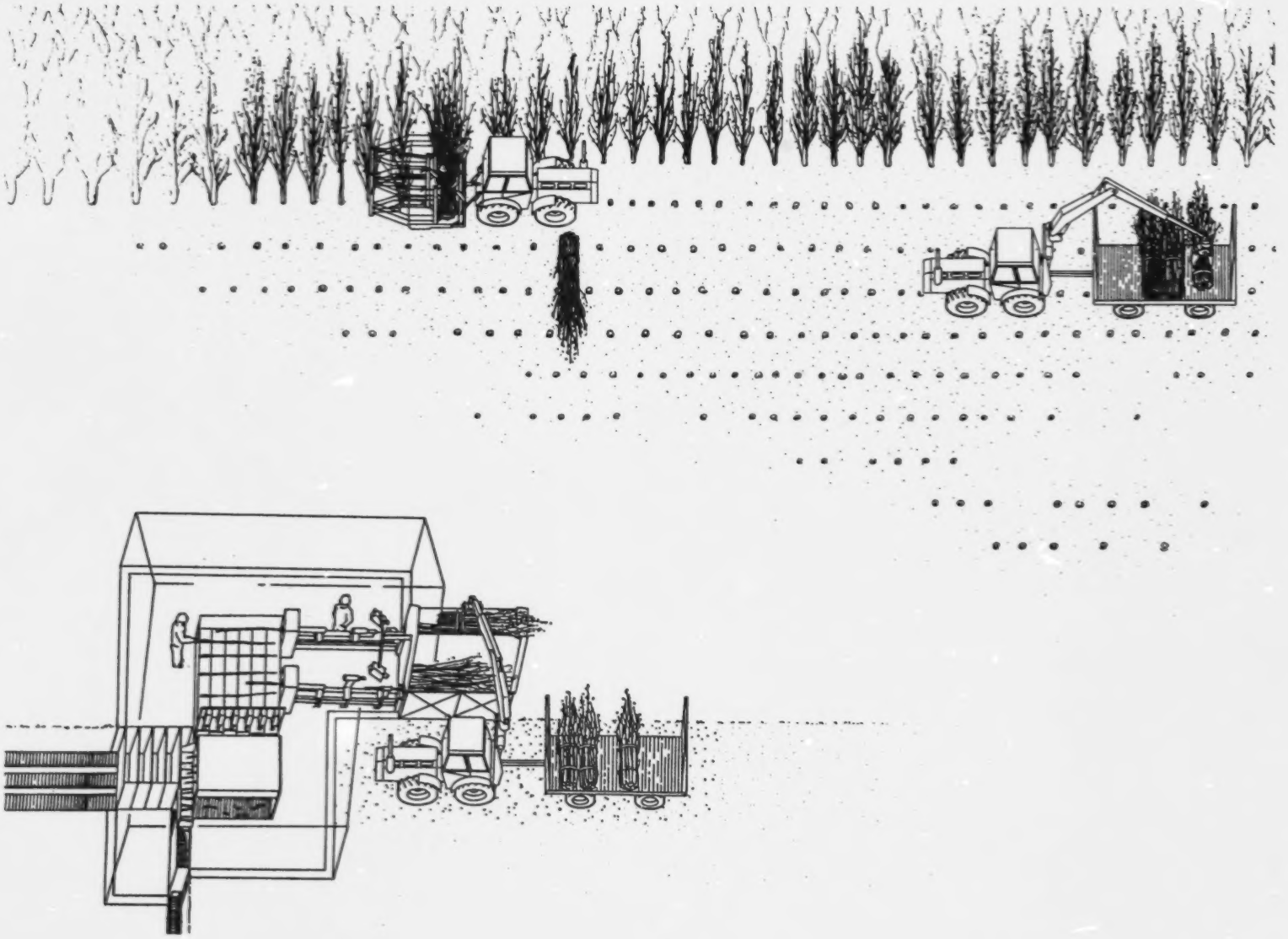

Figure 3. Fully mechanized SRF nursery operations

Production, Handling, and Storage of Cuttings

The bundles of whips are brought into the plant, where the whips are separated, and the limbs and unusable tops are then cut off by hand. The debranching is presently a very costly, labour-intensive operation. The whips are then cut to 25-cm long cuttings, which are inspected for straightness, graded by diameters, and made into bundles. The bundles are sealed in plastic bags to retain the moisture while waiting for the planting operation. The bags of cuttings are put in cold storage where they are kept dormant until the spring planting.

A completely automated production of cuttings was under study by the NRCC.[1] The proposed production operation is illustrated in Fig. 3.

PLANTING OPERATIONS

The planting operation is illustrated in Fig. 4. This is a completely mechanized operation, including a fully automated planting machine under development by the NRCC.[2]

Handling of Cuttings and Planting

Early in the spring, just after the spring break-up, the planting operation begins while the ground is still cold and wet. The cold and wet soil encourages the development of roots before the buds start growing. The operation is labour intensive and very slow because the distance between the rows and between the cuttings must be kept constant. Modified transplanters and specially designed 3- and 4-row planters have been built, where people sit on the planter facing to the rear of the machine and drop cuttings into the furrow made by the disk just ahead of the planters. The operation is tiring if a high productivity is expected. This approach applies mainly to the 1- and 2-year rotation plantations, where more then 33 000 cuttings must be planted per hectare. The workers planting cuttings on such a machine can plant about 1200 cuttings per hour; however, they must be changed or replaced often if high productivity is required throughout the day.

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[1] Bedard, J.T. 1985. Production de boutures de peupliers. Centre de Recherche Industriel du Québec, Quebec. NRCC Int. Rep. Contr. No. OSX83-00150.

[2] Hussey, K., and Doel, R.G. 1985. Automatic planter for hybrid poplar plantations. Forest Machinery Co., Dundas, Ontario. NRCC Int. Rep. Contr. No. OSX83-00105.

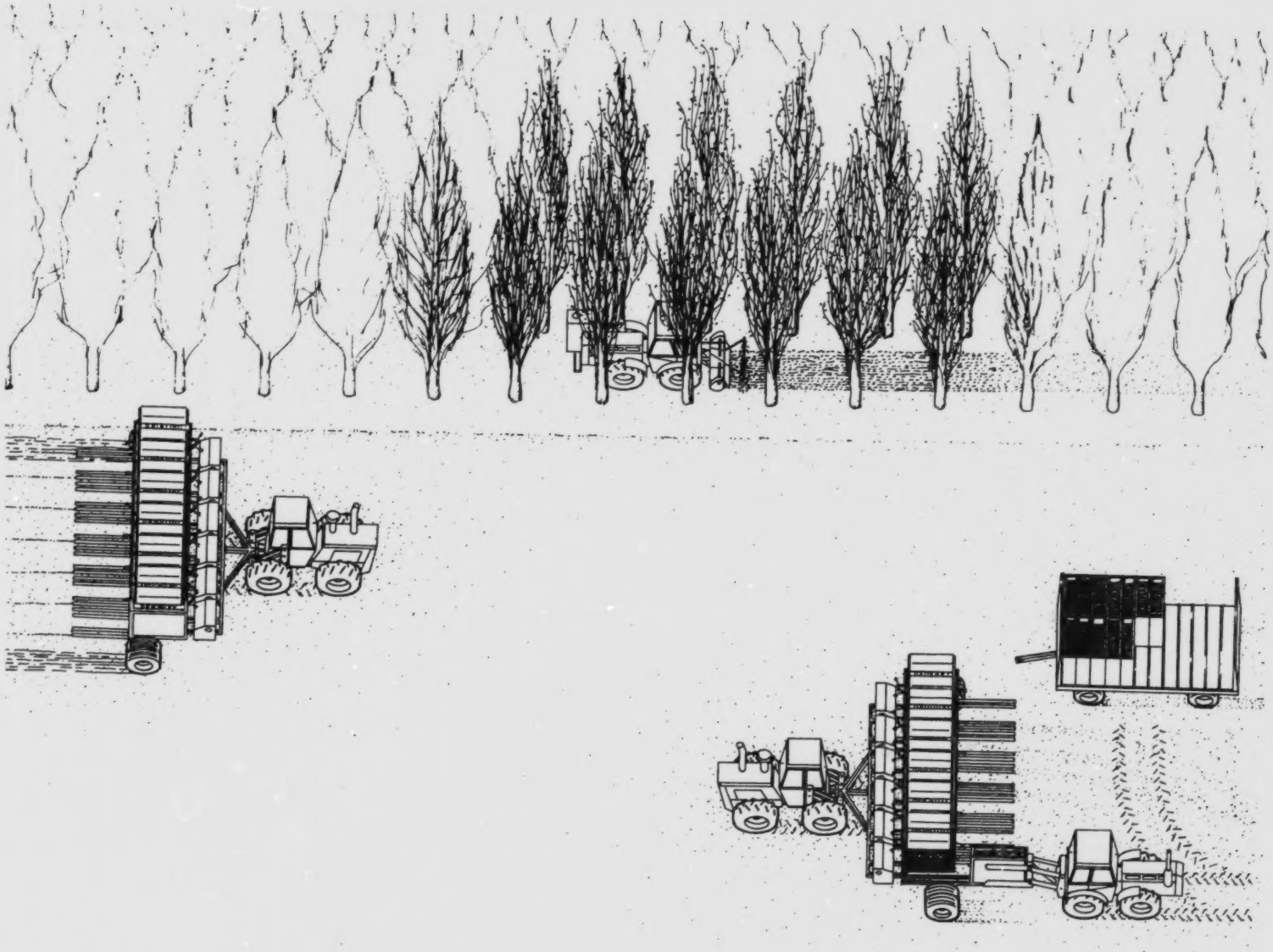

Figure 4. SRF planting and tending operations

Planting of 5- and 10-year rotation plantations is done by hand, because of the wider spacing between the rows the existing transplanting machines cannot be adjusted to accomodate the 1.5- or 3-m spans.

TENDING OPERATIONS

Chemical Weed Control

The equipment for the application of chemicals during the tending operation may need modifications to accommodate different spacings between the rows of trees for given rotation periods. Also any application of chemicals in the first year of the 1- and 2-year rotation systems would require high clearance equipment or attachments, so that several rows of trees can be treated in one pass. The application depends on the type of predominant weeds in the plantation and may vary between different parts of the same plantation. The chemical and the rate of application is determined by site conditions.

Mechanical Weed Control

As in the case of the chemical weed control equipment, the spacing of trees will determine the type of equipment that can be used. The existing equipment may not be economically acceptable if it would require more than one pass to cultivate one space between two rows, which means the cultivating machines will require modifications and redesign to accommodate the plantation requirements. A mechanical cultivating operation is illustrated in Fig. 4.

The cost of tending operations is high, in particular if it involves weed control chemicals. The spacing governs the coverage per one pass, which in terms of hectares per hour is quite small.

The application of fertilizers can be done at the same time as the cultivation, or it can be applied separately; however, if both are required, the two passes would be too costly.

HARVESTING OPERATIONS

Some researchers have analysed the various phases of SRF harvesting operations;[1] Curtin and Barnett, 1985); this study looks at all aspects of

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Spanjer, D.L. 1982. Study and analysis of harvesting systems. David I. Spanjer & Associates., Toronto, Ontario. NRCC Int. Rep. Contr. No. OSX82-00119.

SRF hybrid poplar plantation harvesting, including different rotations and different yields per hectare.

Small Dense Growth

The spacing of trees in 2- and 3-year rotation plantations is as close as 0.3 m, and the rows are 1 m, or less apart. The first or subsequent harvesting present difficulties because of the density of growth. If harvesting is done by hand it is very slow and labour intensive. Some reports suggest the use of multi-functional machines that will fell and chip the biomass and blow the chips into the transport for shipping to conversion site (Moran and Nautiyal, 1985). It is hard to visualize the highway transport vans following the harvester through the plantation. Our studies concluded that we cannot use the highway tires in the field, and likewise the field tires cannot be used on the highway, unless the transport travels on the highway at not more then 10 km/h.[1] At the landing the chips would be transferred into the highway vans for delivery to the conversion point. If the chips are left at the landing for any length of time they would rapidly degrade. Also the chips would still have to be collected and loaded into highway vans at a later time. The transfer and handling of chips is a very costly operation. Chipping in the field is also a very slow and costly operation. Such a multi-purpose harvester would require a large tractor that would have at least 100 kW of power available for the chipper and for cutting and conveying devices, or it would need a separate power plant for the chipping operation. In any case the machine would be costly and quite slow to operate.

The operation should produce bunches or bundles of biomass deposited in the field as harvested, and later taken to the landing at the roadside where the bundles can be left in piles until the biomass is scheduled to be chipped and delivered to the conversion point. While waiting for chipping, the bundles of trees would air dry sufficiently for the chips to be further processed without the additional drying expense.

Small Single Trees

The first harvest of the 5- to 7-year rotation plantation will yield trees of approximately 10-cm stump diameter and about 9-m height. These trees weigh an average of 26.5 kg. At an estimated rate of survival of 85%, the plantation will possibly yield 50 ODt/ha. The harvesting operation that will cut and bunch these trees is different from the operation in

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[1]Walker, L. 1982. Feasibility study and design concepts for hybrid poplar biomass transportation system. Lloyd Walker Consulting Ltd., Ottawa, Canada. NRCC Int. Rep. No. OSX81-00124.

the dense 2-year rotation plantation, because of the different physical characteristics of the two crops. The machines that will harvest and bunch these small trees must be highly productive to meet the required economic criteria, because of the small biomass yield per tree. Also, the bundles of trees must be taken to the landing by machines designed especially for that task. The spacing between the trees and between the rows of a 5-year rotation plantation in Eastern Ontario is 1.5 m. The trees can be harvested manually with chain saws or by using a conventional feller buncher harvester. The bunches are then skidded to the landing; the operations within the system can be carried out at different times, since they are not interdependent. This approach provides for inventory storage between operations, thus allowing for the optimization of the overall operation. However, to be cost competitive, a SRF harvester for harvesting small diameter stems must harvest trees at a rate 7 to 10 times that of existing equipment (Curtin and Barnett, 1985).

A machine designed to increase the harvesting productivity in small trees is the NRCC FB7 continuous feller buncher, which produced within a row 1057 trees per hour (Curtin and Barnett, 1985).[1] The single small tree harvesting operation is illustrated in Fig. 5. The proposed 4-row harvester shown in the illustration is based on the design of FB7 which is a single-row prototype.

Large Single Trees

When referring to large plantation trees, this study refers to hybrid poplar plantations of 8- to 12-year rotations. In a 10-year rotation plantation in Eastern Ontario the trees within a row are spaced 3 m apart and the distance between the rows is also 3 m. The average tree is estimated to weigh 136 kg. It has an average diameter of 25 cm and is approximately 15 m tall. At a rate of survival of 85%, the plantation will yield 64 ODt/ha, for a mean annual production of 6.4 ODt (Anon, 1980).

The harvesting of these large trees can be done by using conventional forest harvesters and skidders. However, the row crop type of an arrangement of hybrid poplar plantations is well suited to the continuous harvesting techniques illustrated in Fig. 6. The harvesting machine shown in the illustration is a 2-row attachment to a large tractor, based on the work

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[1] Stokes, B.J., Frederick, D.J., and Curtin, D.T. 1985. Short rotation biomass harvesting system evaluation. Unpublished Report. Southern Forest Experiment Station, U.S. Forest Service, G.W. Andrews Laboratory, Auburn, Alabama, U.S.A.

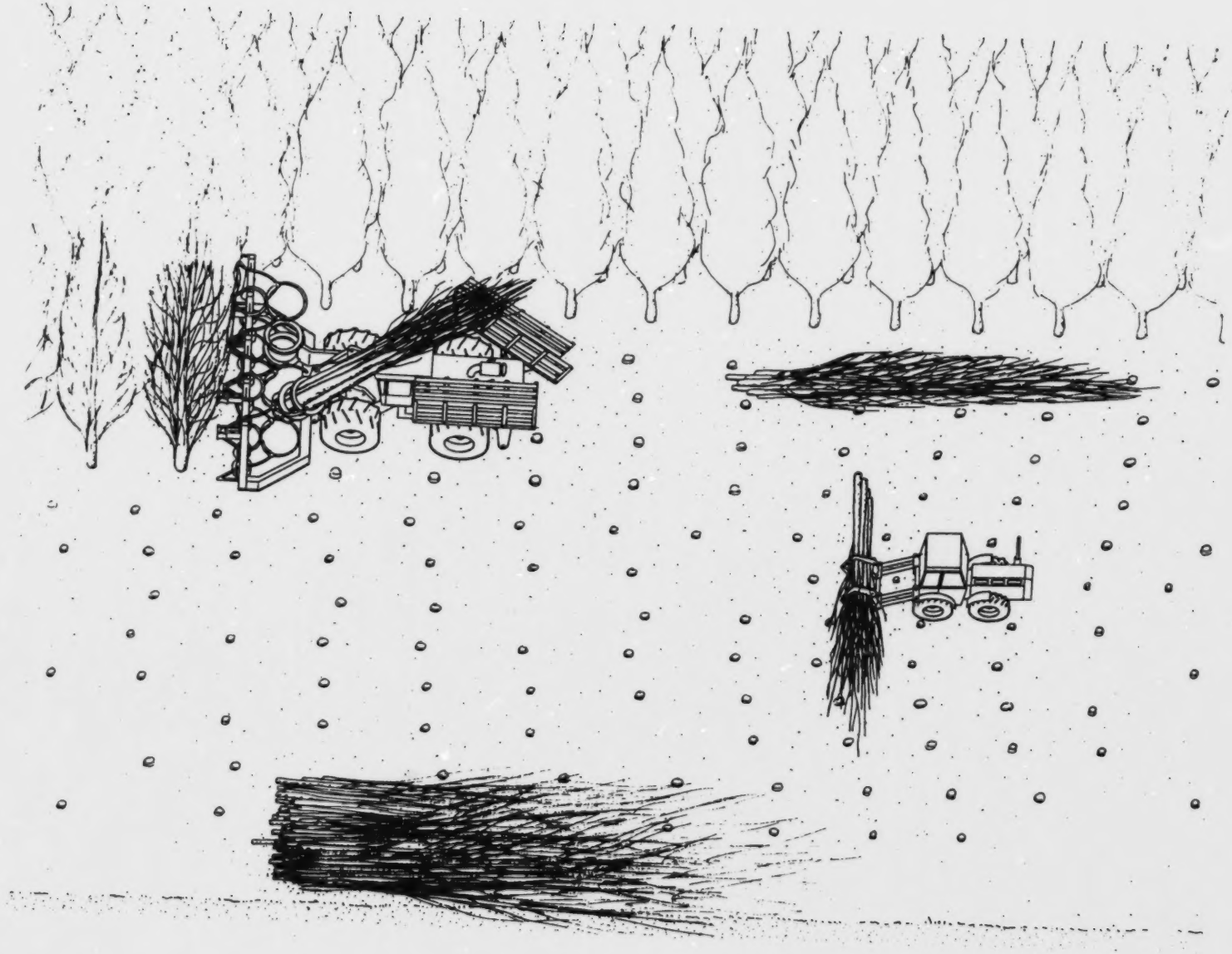

Figure 5. SRF harvesting operations - 4-row harvester

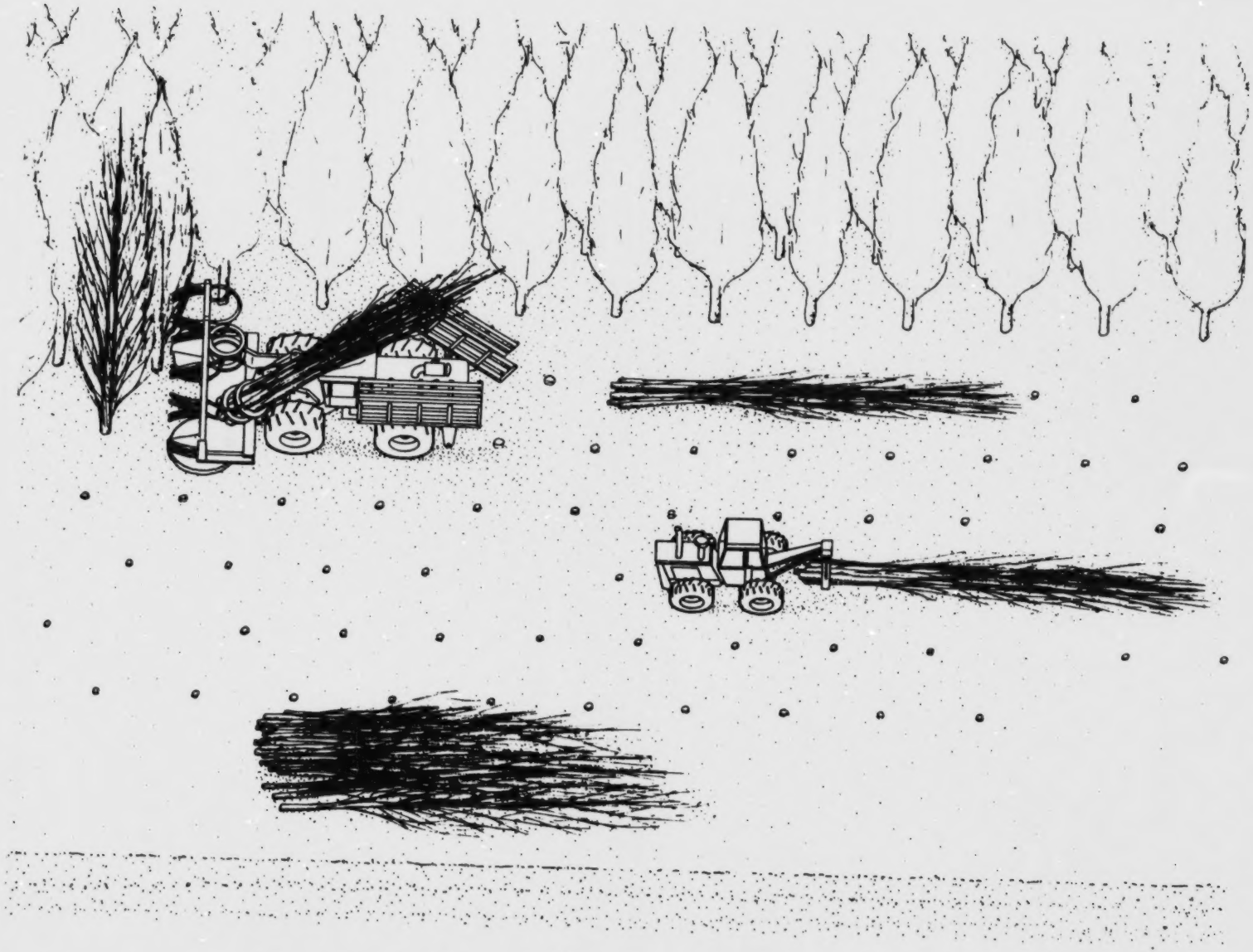

Figure 6. SRF harvesting of large trees - 2-row harvester

done by the NRCC.[1] The machine under development is a single row harvester. The bunches of trees are normally skidded to the landing at the roadside, where they are piled and left to dry, to be chipped at a later date.

Coppice Growth

It was assumed that the coppice growth of 5- and 10-year rotation plantations may require a different machine system because of multiple stem growth coppiced from the original stump. There is very little information on the statistics of these coppice grown trees; some studies indicate a possible one to three stems remaining at year 5 and only a single stem at year 10.[2] These reports may indicate that for a 10-year rotation the single stem harvester could be used on subsequent harvests. Also, the 5-year rotation coppice harvester would harvest trees of a size close to the first rotation single stem plantation trees, with possibly two tertiary stems of smaller diameter per coppice. The present thinking calls for the operation that would cut and bundle coppiced trees in a continuous operation, which was incorporated in the harvesting machine under development by the NRCC.[2]

CHIPPING AND TRANSPORTATION OPERATIONS

Chipping

The chipping operation can be done in the field combined with harvesting, at the landing at roadside as an independant operation, or at some other conversion point. In this study the chipping is assumed at the roadside landing, mainly because it is considered the most economic operational system, because it provides an intermediate inventory stockpile for a more efficient scheduling, and because it is assumed the chipping is done by highly mobile chippers, which can be moved relatively rapidly from plantation to plantation (Crossley and Sullivan, 1980; Short and Kipping, 1983). Also, it provides the opportunity for biomass to dry before chipping and delivery to the conversion point. A typical chipping operation at the roadside landing is illustrated in Fig. 7. The productivity of the

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[1] Jasinski, S.K., and Robb, D.S. 1984 . Development of a harvester for ten year old hybrid poplar plantations; Feasibility study and concepts. HYD-MECH Forestry Ltd., Woodstock, Ontario. NRCC Int. Rep. Contr. No. OSR84-00078.

[2] Gordon, D., and Voss, D. 1984. Feasibility study for the design of a coppice harvester for hybrid poplar plantations. J.D. Reed Machine Limited, Brantford, Ontario. NRCC Int. Rep. No. OSR84-00080.

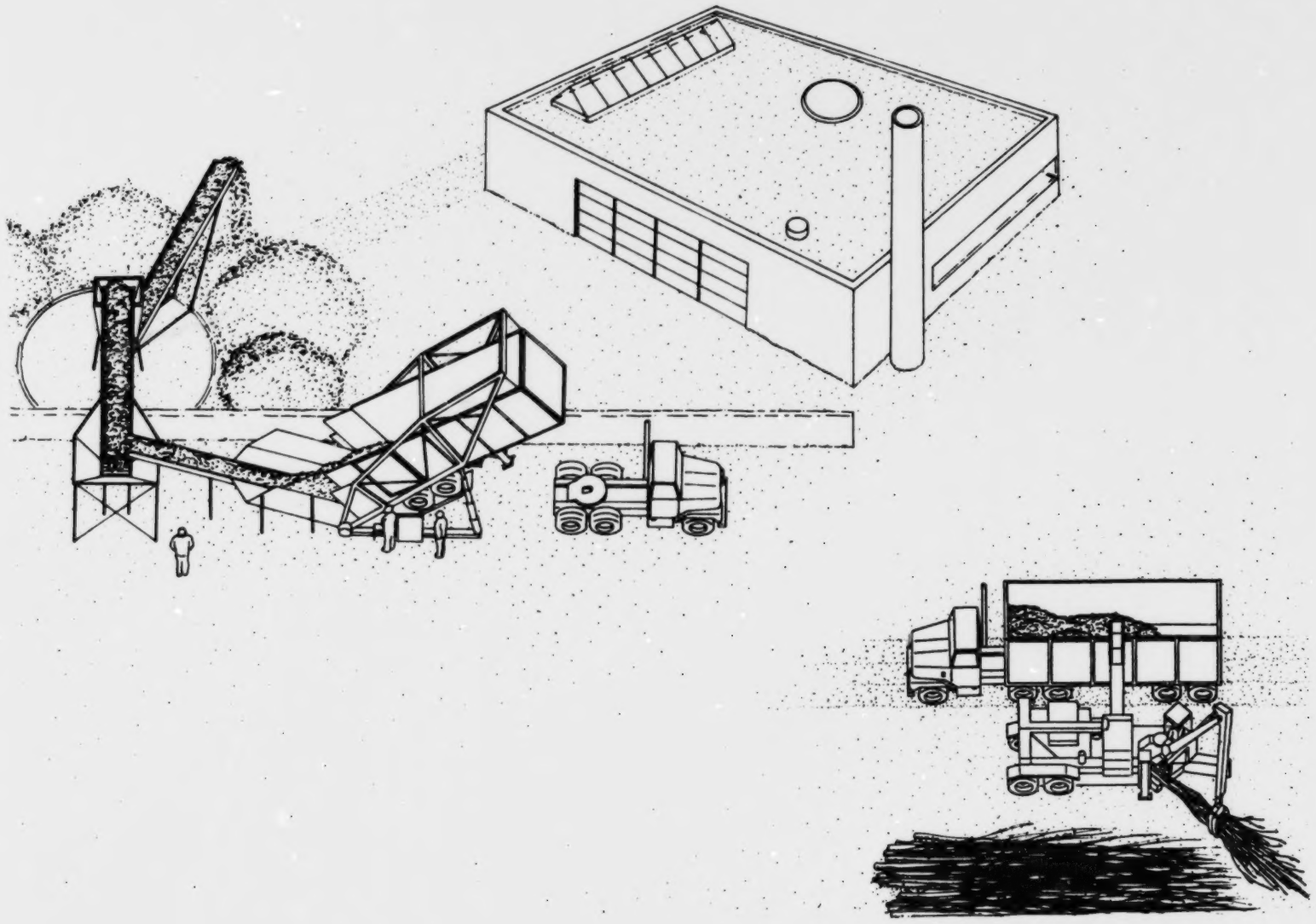

Figure 7. Roadside chipping and transport operations

chipping operation is normally only a fraction of the theoretical capacity of the chipper. The feeding efficiency depends on the sizes of trees and bunches or bundles of trees; also, the reach of the loader and the organization of the pile of trees will affect the feeding efficiency. The numberof spare trailers and the delays in changing trailers accounts for a large percentage of the overall reduction of the chipping efficiency.

Transportation System

The transportation of trees or chips has always been considered as one of the costliest operations in forestry. The transportation of chips in a SRF operational system is the third costliest operation, depending on the extent of the mechanisation of other operations. The type of equipment is assumed to be that of forest operations. However, in this study, the size of chip vans is taken as maximum for the provincial highway regulations, which includes the large highway tractors capable of pulling fully loaded 14-m-long chip vans. The advantage of the location of hybrid poplar plantations is in better road systems close to major cities. In this study the average distance to the conversion points and the average road speed was optimized; also the number of vehicles on the road at one time was balanced with the production of chips, the distance, and the road speed of the vehicles. The loading and unloading delays are most important for the efficiency of the overall system (Anon, 1984).[1] The unloading is assumed to be done with mobile unloading frames illustrated in Fig. 7.

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[1] Walker, L. 1982. Feasibility study and design concepts for hybrid poplar biomass transportation system. Lloyd Walker Consulting Ltd., Ottawa, Canada. NRCC Int. Rep. No. OSX81-00124.

COST AND PRODUCTIVITY

The overall analysis of costs reflects the industrial engineering analysis of operations, where the main objective remains the most desired synthesis of all of biological, operational, economical, and technological input variables; also, the relative sensitivity of various inputs has been analyzed in a general sense. Input variables were in most cases estimated, however, and, if anything, these estimates are conservative, making the projected costs low, rather then high.

The productivity of individual mechanical systems was computed, based on established technical criteria and on estimates of operational factors. Each operation was treated separately in as much detail as is practical.

There are two parts to the analysis, the individual operations are computed in dollars per hour, and the final cost of the total system was converted to the cost in dollars per oven dry tonne in the second study.

COMPUTATIONS

In a general sense, costs are computed using established accounting algorithms, following accepted financial practices. The operational productivity computations were done by using equations developed for this particular analysis.

Capital Cost

All capital costs were computed by applying an equation published by the Canadian Pulp and Paper Association (Rickards and Savage, 1983). This expression uses the capital recovery factor (Edge, 1965) following:

$$CRF = \frac{i(1 + i)^n}{(1 + i)^n - 1}$$

where

i = real discount rate
n = machine life in years

The capital cost equation shown below is that before taxes; this method was chosen on the grounds of a survey of the members of the CPPA, who expressed their opinion that this method is the best one available, because it does not include any tax credits. Also, it is not subject to any fixed capital cost allowance (Rickards and Savage, 1983). Another study states that the before-tax cost equation can be sufficient to estimate the typical worth of a variety of individual cases, provided the

correct discount rate relevant to the specific case is used.[1] The interest rate in these computations is real, giving costs in constant 1985 Canadian dollars, disregarding the future rate of inflation.

$$CC = (C - R)\frac{i(1 + i)^n}{(1 + i)^n - 1} + (Ri)$$

where

CC = cost of capital
R = residual value at the time of replacement
C = purchase price of the equipment
n = life of the machine in years

The above expression for the cost of capital or capital recovery depreciation (Rickards and Savage, 1983) evaluates the cost of investment and the recovery of its full value over the economic life of the investment. In the first part of the equation the capital recovery factor is applied to the initial investment less the residual value of the equipment in present dollars. The second part of the expression represents the return on the residual value at the given rate of interest.

Interest Rates

The interest rate relevant to any firm's demand for capital is the real rate, because it is not affected by any future variations in the rate of inflation, which could conceivably bring the real rate to zero in the case where the nominal interest rate is used and where the rate of inflation increases beyond the anticipated inflation (Dornbusch and Fischer, 1981). Also, it is often simpler and more realistic to simulate a future investment in real or constant terms.[1] These constant terms refer to the real rate of return on investment, or real discount rate, also referred to as the opportunity cost of capital.

The interest rates used in this analysis are real rates of return, disregarding the effect of any future inflation. In calculations of normal or, as addressed in the study, low costs, the real rate of return used is 7%, also referred to as the social discount rate.[1] The social rate of return is also called the weighted average rate of return; this is a minimum rate of return on total capital, including borrowings and equity, representing a constant mix of funds.[1] When the rate of inflation of say 4% is added to this rate we have a nominal rate of return of 11%.

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[1] Pigeon, R. 1985. Costing short rotation forestry at NRC's Bioenergy Program. National Research Council of Canada, Ottawa, Ontario. NRCC Internal Report.

In calculations of adverse, or high costs, the rate used is the weighted average industrial discount rate of 10%. The suggested range of real private or industrial discount rates before-tax is 9% to 15%.[1] The rate of 10% provides the information on sensitivity in the variation in discount rates; also, it reflects an alternative in the real world. If a rate of inflation of 4% is added to the industrial discount rate we have a nominal discount rate of 14%.

Equipment

The cost of various machine systems, which include different tractors, attachments, and other mobile equipment, was computed under two separate groups. Tractors are normally used in conjunction with many different agricultural operations, as well as on forest plantations. They are assumed to be fully utilized throughout the year; their yearly productive machine hours are quite high. On the other hand, the attachments developed for SRF plantations are used only for specific operations, and within a relatively short time interval in a given season. These specialized machines and equipment will reflect much shorter yearly usage.

The price of tractors is based on list price estimates for required sizes of tractors. Prices of all tractors in a given operation were added together, and a range of prices was established within a limit of approximately ±10% of the estimated total of all list prices.

These ranges of prices were then used to compute the cost of capital by using the expression described above. The computations were done for 10% increments, starting with the low price range. The computed costs were divided by the number of productive machine hours (PMh) per year, which were taken as 75% of the scheduled machine hours.

The cost of attachments and equipment is computed in the same manner as that for the tractors, except for the much smaller number of scheduled hours applied to the attachments. The yearly hours vary with the operation. Harvesting can be done from the month of October to the end of March; however, the time interval for the planting operation is only about 6 weeks long. The duration of other operations varies considerably because of the seasonal constraints.

In the computations of the capital cost the exponent n, the life in years, is taken for tractors as 12 years when computing the normal, or low

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[1] Pigeon, R. 1985. Costing short rotation forestry at NRC's Bioenergy Program. National Research Council of Canada, Ottawa, Ontario. NRCC Internal Report.

cost, and 10 years for the high cost input. The same figures for the computations of the costs of the attachments are 8 and 6 years.

The low range of the scheduled machine hours for tractors was taken as 1000 to 1400 and the high range as 1200 to 1600 h. The low scheduled hours were used to compute high capital costs and the high hours were used to compute the low capital costs for each increment of 10%, starting with the total of low prices. The high values of the two ranges, 1400 and 1600 h, were used to compute the productive machine hours and the cost of capital.

Insurance and Shelter

The cost of the insurance was computed as $0.50 per each $100.00 of the total price of machines; and the cost of the machine shelter was taken at 1.5% of the machine price range (Anon, 1975). The yearly cost of the shelter and insurance was then added to the computed cost of capital.

Labour and Overhead

Labour wages were taken as $11.00 per scheduled machine hour or $14.66 per productive machine hour, which was taken as 75% of the scheduled machine hour. Overhead or burden was applied to the labour at a rate of 25% for low or normal costs and 30% for the computation of high operational costs.

Energy

The cost of energy is basically the cost of engine fuel per hour of machine operation, plus, in the case of the cost of nursery production of cuttings, the cost of electricity used per hour of operation. The expression used to compute the consumption of fuel was developed by Nebraska Tractor Tests. The average power output of a tractor in varying power tests is approximately 54% of the maximum power take-off (pto) power; and the approximate fuel consumption is expressed in the following formula.

$$Q = \frac{0.54P}{kWh/L}$$

where Q is the average fuel consumption in litres per hour and P is the maximum pto power of the tractor expressed in kilowatts. The expression kWh/L indicates average power output per litre of fuel, which is given by Nebraska Tractor Tests as 2.43 kWh/L of diesel fuel (Liljedahl et al., 1979). The cost of a litre of diesel fuel is taken as $0.46; the cost of electric power is $0.0476 per kilowatt-hour of use.

Equipment Repair

There are many different estimates of the cost of repairs of agricultural equipment. The agricultural engineering department of the University of Illinois and the Agricultural Engineering Yearbook quote 90% of the original price as repair cost for tractors at accumulated 10 000 h of use. The same source quotes the cost of repairs as 75% of the original price for planters and drills at 1000 h and 80% for plows at 2000 h of use (Anon, 1975; Bowers, 1975; Buth, 1981). Other sources quote either higher or considerably lower percentages. In this analysis the cost of repairs for tractors was taken as 90% for the low cost computations and 100% for the computation of high operational costs. Similarly, for the attachments these percentages were, in most cases, 80% and 90%.

Service and Supplies

Under supplies are included such things as oil, grease, oil filters, and tires. The cost of grease, oil, and filters is estimated to be 10% to 15% of the cost of fuel (Anon, 1975; Liljedahl et al., 1979; Dillon, 1971). In this study, oil, grease, and oil filters are computed as 15% of the cost of fuel per hour.

The cost of tires is computed from actual tire prices and from the estimated life of agricultural and forestry tires. The cost of replacement tires was divided by the expected life of tires in hours. The life of tires varies from 3000 to 5000 h, and prices vary from $360 to $2000 per tire. The cost of tires was added to the cost of oil, grease, and oil filters, thus defining maintenance or service materials. The maintenance labour is computed as a percentage of the total cost of labour, which was then added to the cost of service supplies. The cost of service labour and service supplies was identified in the cost of operation as the cost of service. The cost of service labour was estimated as 5% of the total labour for the low or normal cost, and 6% for the computation of the high operational costs.

Total Operational Costs

The total operational costs are divided into five cost groups: capital, labour, repair, energy, and service. The relative percentages of individual cost components will vary with the concentration of capital and labour in given SRF operations.

LAND PREPARATION - COST AND PRODUCTIVITY

The land preparation operations are illustrated in Fig. 1, where it was assumed that the land was covered with brush before the land preparation operations began. Cost and productivity of all land preparation operations were analyzed separately, then the individual sub-system information data were combined in the final cost analysis of the whole land preparation system. This total cost is expressed as cost per productive machine hour of the whole operational system, so that costs for all SRF operations can be treated in the same manner.

The productivity of various land conversion operations was computed by using the following expressions.

$$THW = \frac{SPD \times 1000}{LNG/WDT \times 10\ 000/LNG}$$

where

THW = theoretical productivity in hectares per productive machine hour
SPD = ground speed of the equipment in kilometres per productive machine hour
LNG = length of the machine run in metres
WDT = working width of the machine system in metres

The second expression computes the delay due to turns.

$$DEL = \frac{TRN[(SPD \times 1000)/LNG]}{3600}$$

where

DEL = delay in a fraction of an hour
TRN = delay per turn in seconds

The third expression converts the theoretical productivity to the actual productivity, corrected for the delay per turn.

$$ADW = THW(1 - DEL)$$

where ADW = adjusted productivity in hectares per productive machine hour.

The productivity for the whole system is calculated at 0.4 ha/PMh based upon a ground speed of 2.5 km/h, an average length of run 100 m, and a delay at turns 30 s per turn. The productivity of land preparation operations is illustrated in Fig. 8. An increase of 10 s in the delay per turn for the given length of run and ground speed will reduce the productivity by approximately 0.03 ha/PMh.

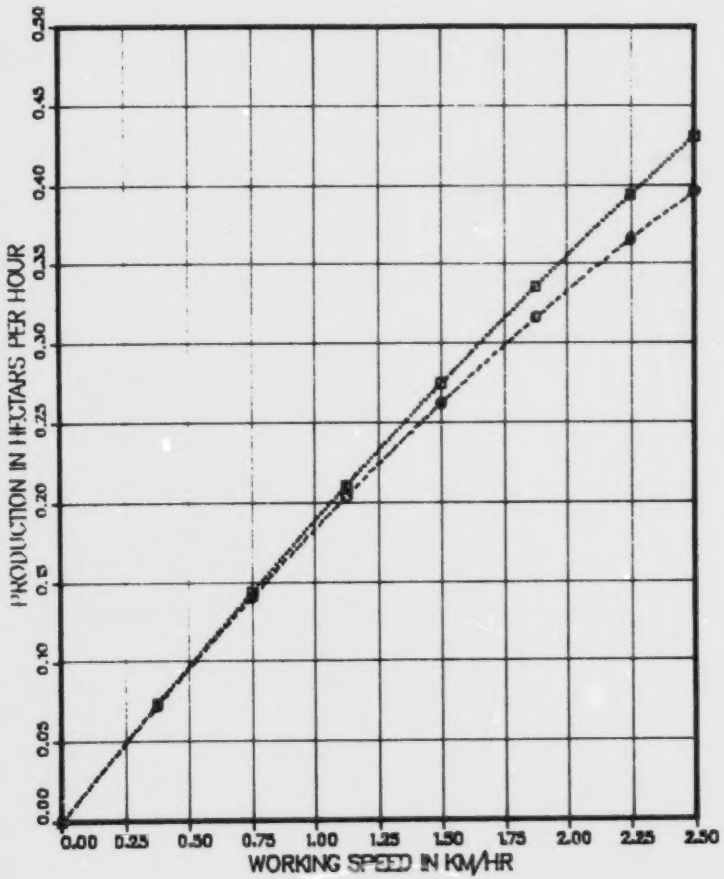


Figure 8. Productivity analysis of a land preparation operation system

However, at a ground speed of 5 km/h, an increase in the delay per turn of 10 s will decrease productivity by approximately 0.14 ha/PMh, and it will become counter-productive at a ground speed of 4.5 km/h for the delay of 40 s per turn, and at 3.5 km/h for the delay of 50 s per turn.

The productivity is affected directly and proportionally by the width of work. As the length of run increases, the delay per turn becomes less significant, at a 500 m length of run, a delay per turn of 30 s, and at a ground speed of 2.5 km/h, the productivity increases only by 0.08 ha/PMh, as compared to an almost straight line increase at a run of 100 m shown in Fig. 8.

Brush Removal

The brush is harvested by a brush harvester illustrated in Fig. 1, and the bundles of brush biomass are taken to the roadside by two front end pilers. The brush biomass is intended to be chipped and sold, to compensate partly for the cost of the land preparation.

Brush is harvested by an attachment to a medium-sized tractor. The tractor used for the analysis is a four-wheel drive vehicle, with a maximum pto power of 63 kW. The list price of the tractor is $45 500.00; however, the productivity of the brush harvester is less than the assumed productivity of the land preparation operation, because the width of work is only 1.75 m compared to 2 m taken for the whole operation. The correction factor was computed as 0.87, which increases the input price to $52 298.00, equivalent to 1.15 tractors. The pto power was also corrected to 72 kW.

Forwarding is done by two small tractors equipped with front-end piler attachments. Tractors are small, four-wheel drive vehicles having 45 kW maximum pto power, or 90 kW total for the sub-system. The list price of forwarding tractors is $33 600.00 per vehicle or $67 200.00 for the two tractors.

The replacement tires for the harvester tractor were taken at a list price of $468.00 each. For eight tires with a life of 5000 h, the tire replacement cost is $0.87/PMh. The two forwarder tractors are equipped with a total of 16 tires; at a price of $360 per tire the replacement cost is $1.15/PMh.

These cost inputs were added to the costs of other tractors for the total system cost.

The cost of the harvesting attachment was estimated at $25 000.00 and corrected for the productivity, due in part to its width of only 1.75 m, to

$28 735.00. The cost of the front-end pilers was estimated at $7 500.00 each or $15 000.00 for the two devices.

Stumps and Stones

The machine shown in Fig. 1 as it cuts and collects roots and stumps was studied as a possible single pass machine that would remove stumps, roots, and stones. The width of operation is 2 m as designed, which was taken as the basis for the overall system productivity. The list price of the tracked tractor is given as $245 000.00 having a maximum pto power of 108 kW. The price of the root cutting and collecting equipment was estimated at $80 000.00; it has an on-board power plant of 75 kW.

Plowing and Disking

Plowing is assumed to be done with a 6 - 45 cm bottom plow, pulled by a tractor with a maximum pto power of 75 kW at a ground speed of 2.5 km/h. The working width of the plow is 2.7 m, covering 0.53 ha/h, for a correction factor of 1.55. The list price of the tractor is taken as $49 500.00, corrected to $31 935.00, and the price of the plow is taken as $10 500.00, corrected to $6775.00, due to the productivity 1.55 times that of the base set for the land preparation operations.

The disk-harrow is assumed to require four passes at a ground speed of 5 km/h, and for a width of 6.4 m the system covers 1.87 ha/h, for an operational correction factor of 4.67. The list price of the tractor is $45 500.00, corrected to $38 972.00, for an hour of operation making four passes. The tractor is rated at 63 kW of maximum pto power, corrected to 54 kW. The tire replacement cost is $0.64/PMh.

The disk-harrow implement costs $10 500.00, corrected to $8980.00 for an hour of operation, due to the produtivity of 1.87 ha/PMh compared to the base for the system of 0.4 ha/h.

Harrowing and Chemicals

Chemicals can be applied simultaneously with the spring-tooth harrow; however, in this study the harrow makes two passes and the chemicals are applied in a single pass. The spring-tooth harrow is pulled by a small four-wheel drive tractor at a ground speed of 6 km/h; the implement is ,.7 m wide covering 2.01 ha/h, for an operational correction factor of 5.05. The list price of the tractor is $33 600.00, corrected to $13 360.00 for an hour of harrowing. The tire replacement allowance is $0.23/PMh.

The price of the spring-tooth harrow is $7200.00, corrected to $2863.00/PMh.

Chemicals are applied with a 15.2-m wide sprayer at a ground speed of 2.5 km/h, covering 3.01 ha/h, for a correction factor of 7.52. The list price of the tractor is $33 600.00, corrected to $4468/PMh. The price of the spraying implement is $7500.00, corrected to $1995.00/PMh. The chemicals assumed used are "Simazine™ " at $43.75/ha, and "Roundup™ " at $138.00/ha, for a total of $181.75/ha, or corrected for 0.4 ha the chemicals cost $72.70 per hour of spraying.

Total Cost of Land Preparations

The total capital cost input into the land preparation analysis for tractors is $454 233.00, the maximum pto power for the system is 396 kW, and the allowance for the replacment tires is $3.44/PMh. The minimum and maximum tractor price range is taken as $450 000.00 and $480 000.00.

The total cost of implements and attachments is $144 348.00, for a range of $140 000.00 to $160 000.00. The power input is 75 kW and the cost of supplies is $72.70/PMh.

The total corrected labour wages at $11.00 per scheduled operator-hour are $80.63/PMh.

The breakdown of the operational cost per PMh for the whole system is illustrated in Fig. 9; the largest component is the cost of labour at $134.38/PMh, or 33.7% of the total cost of $399.14/PMh. The cost of service is high because of the high input for supplies, including chemicals which are accounted for in the cost of service supplies.

The total cost per hour of $399.14 for a production of 0.4 ha/h, when converted to the cost per hectare becomes $997.85/ha; it takes 2.5 h to prepare 1 ha of land for planting. This cost is based on a real discount rate of 7%, on 1600 scheduled tractor hours, and 1000 h for implements and attachments. The figure for the scheduled implement hours may be high; however, at a factor of 75% the actual productive hours are 750. Also, the operation is assumed to be done by a contractor and not a farmer, which accounts for higher usage of machines.

The high cost of land preparation is $458.98/PMh, which includes several adverse factors such as the real discount rate of 10% and lower scheduled machine hours. At the rate of $458.98 per operating hour, and at the productivity of 0.4 ha/h, the cost per hectare becomes $1147.45; it would take 2.5 h to prepare 1 ha for planting. The high cost of operation is 13% higher then the normal cost per hour.

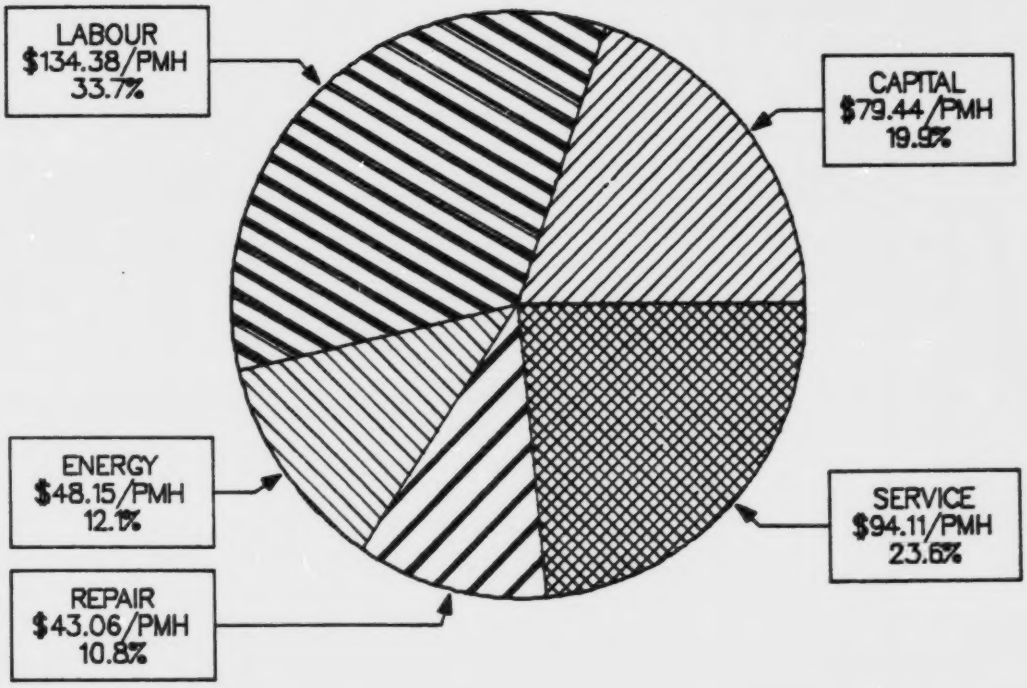


Figure 9. Analysis of land preparation costs. Total low operational cost is $399.14/PMh

NURSERY OPERATIONS - COST AND PRODUCTIVITY

The cost of nursery operations is composed of the cost of whip harvesting, collecting, and delivery to the plant for production of cuttings, and of the cost of the production, packaging, and storing of cuttings. The whip harvesting operation is contracted out, while the production and storage of cuttings stands on its own.

The two operating costs are combined in the final cost of nursery operations. The productivity of the two operations are to a point interdependent; however, they are not dependent in a manner where one operation cannot proceed without the other. For as long as there are sufficient whips in the plant to produce cuttings, the whip harvesting and delivery has no effect.

The harvesting of whips is considerably more productive than the production of cuttings, because there are at an average four whips per coppice and six cuttings per whip, making 24 cuttings from one stump. A single-row harvester will produce approximately 23 700 whips per productive hour,

sufficient for 142 000 cuttings, which is approximately 12 productive hours in production of cuttings, or 2 working days.

Harvesting of Whips

An analysis of whip harvesting productivity is shown in Fig. 10, illustrating the effect that the number of whips per stool makes on the productivity of the harvester.

The productivity is computed in two steps: the biological productivity per hectare is applied to the machine productivity per hectare in the following expressions.

$$THB = \left(\frac{100}{SPR} \times \frac{100}{SPT}\right) \times WHP$$

where

THB = theoretical biological productivity per hectare
SPR = spacing between rows in metres
SPT = spacing between trees in metres
WHP = average number of whips per coppice

The theoretical biological productivity is adjusted by multiplying it by the rate of survival.

$$ADB = THB \times SRV$$

where

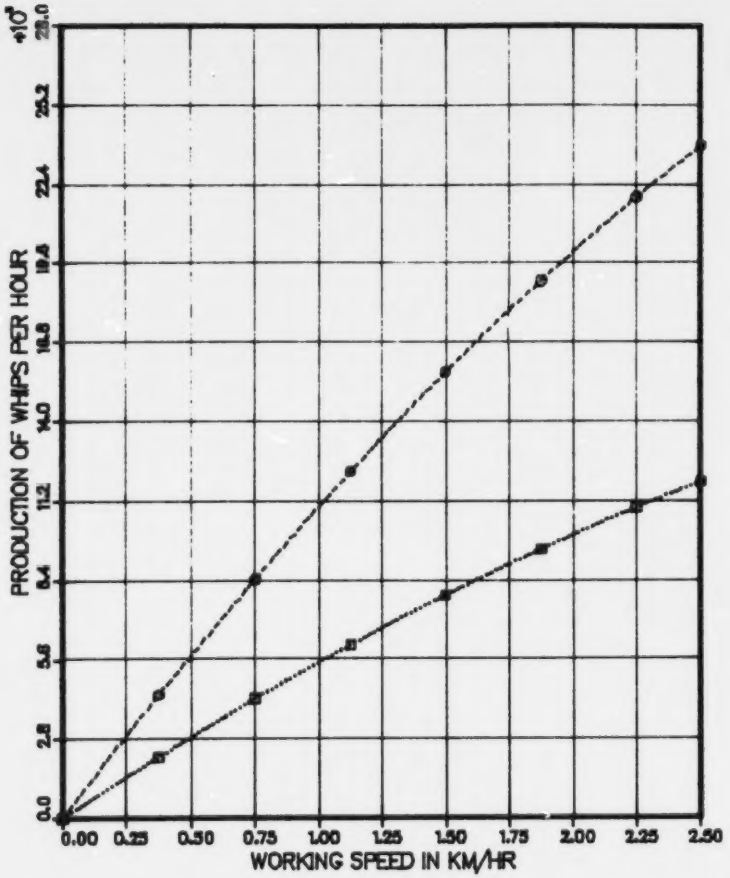
ADB = adjusted biological productivity
SRV = the rate of survival expressed as a fraction of 100%

The machine productivity is computed by using the three expressions used to compute the land preparation productivity. These expressions are explained in the section on Land Productivity. The adjusted biological productivity is then multiplied by the adjusted machine productivity.

$$WPH = ADB \times ADW$$

where

WPH = number of whips harvested per productive machine hour
ADB = adjusted biological productivity, whips per hectare
ADW = adjusted machine productivity, hectares per productive machine hour



SPACING BETWEEN ROWS IS 1.00 METERS--

SPACING BETWEEN TREES IS 0.30 METERS--

AVERAGE USABLE LENGTH OF WHIPS IS 2.25 METERS--

LENGTH OF CUTTINGS IS 25 CENTIMETERS--

LENGTH OF PLANTATION ROWS IS 100.00 METERS--

WORK DELAY PER TURN IS 30 SECONDS--

TREE SURVIVAL IS 90.00 PERCENT--

WORKING SPEED IS 2.50 KM/HR--

ROWS WORKED SIMULTANEOUSLY 1--

LEGEND

□ NUMBER OF WHIPS PER STOOL IS 2--

○ NUMBER OF WHIPS PER STOOL IS 4--

Figure 10. The productivity analysis of a single row whip harvester

In this study the production of the whip harvesting operation, with a single row harvester, is approximately 23 750 whips per productive machine hour. The ground speed of the harvester is 2.5 km/h, and the rate of survival is taken as 90%.

The whip harvesting and collecting system is illustrated in Fig. 1, showing one harvester and one forwarding tractor equipped with a hydraulic loader and pulling a field wagon for transporting whip bundles to the production plant for cuttings.

The cost of the two tractors is $33 600.00 per tractor, or $67 200.00 for the two tractors. The cost of replacement tires is $1.15/PMh. The two tractors have a total maximum pto power of 90 kW. The low and high ranges for the cost of tractors are $70 000.00 and $80 000.00. The cost of the harvesting attachment is estimated at $25 000.00, and the cost of the loader and wagon is $17 500.00, for a total for the attachment and implements of $42 500.00. The low and high price ranges are $40 000.00 and $50 000.00.

The cost of replacement tires for the wagon and the cost of hydraulic oil are estimated at $1.58/PMh; these costs are included under the service portion of the total cost.

The cost analysis for the whip harvesting and transport operation is illustrated in Fig. 11, where the cost of labour of $55.00 represents 54.4% of the total of $101.18 for the normal or low cost of the operation. A proportionally high labour input is due to the relatively low cost of the two tractors and their attachments or implements.

An analysis of the whip harvesting costs based on adverse operational and financial conditions, such as higher interest rate, lower number of scheduled machine hours, higher rate of repair, and a lower salvage value, shows an increase of approximately 12% over the cost based on normal operational and financial inputs. As in the case of the lower cost, the cost of labour of $57.20 amounts to 48.3% of the total cost of $118.48.

At the expected cost per hour of $101.18, the cost per hectare is $505.90. The cost per hectare is high because of a low productivity of only 0.20 ha/h for a single row harvester. The cost of the high cost system is $592.40.

Production, Handling and Storage of Cuttings

In the illustration in Fig. 1 the nursery operation is shown with a tractor equipped with a loader for handling bundles of whips and loading them into the bins.

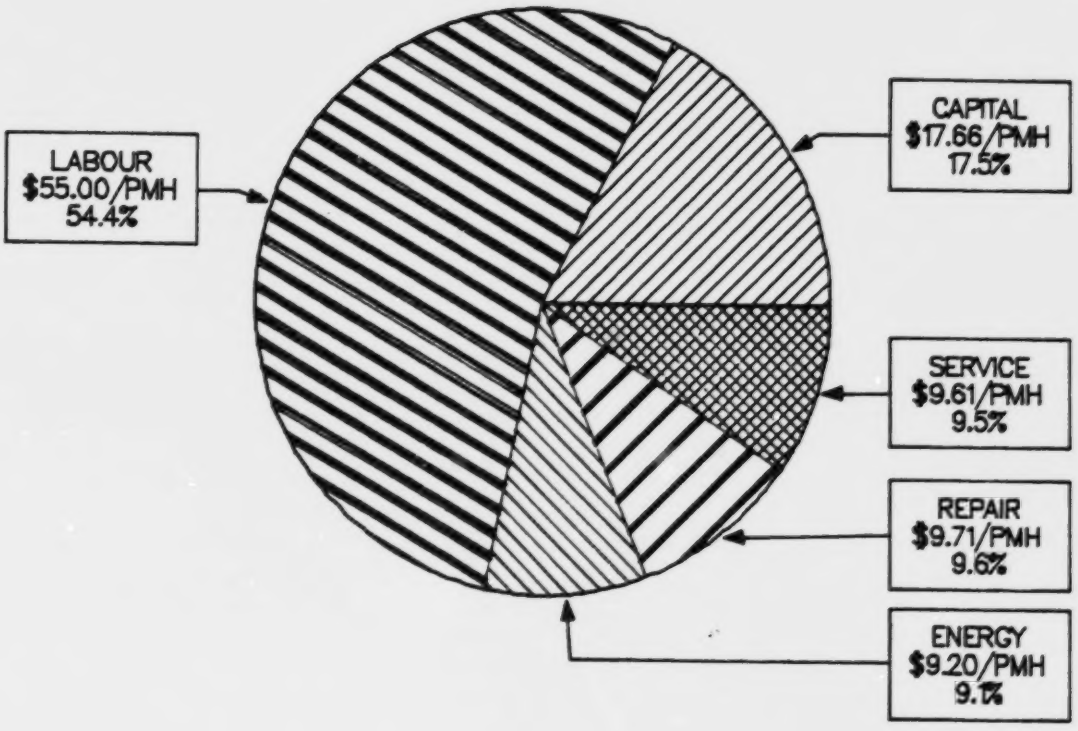


Figure 11. The analysis of whip harvesting costs. Total operational cost is $101.18/PMh

The productivity of the nursery production of cuttings operation is illustrated in Fig. 12, showing the variation in productivity by varying the number of whip delimbing heads from two to four to six.

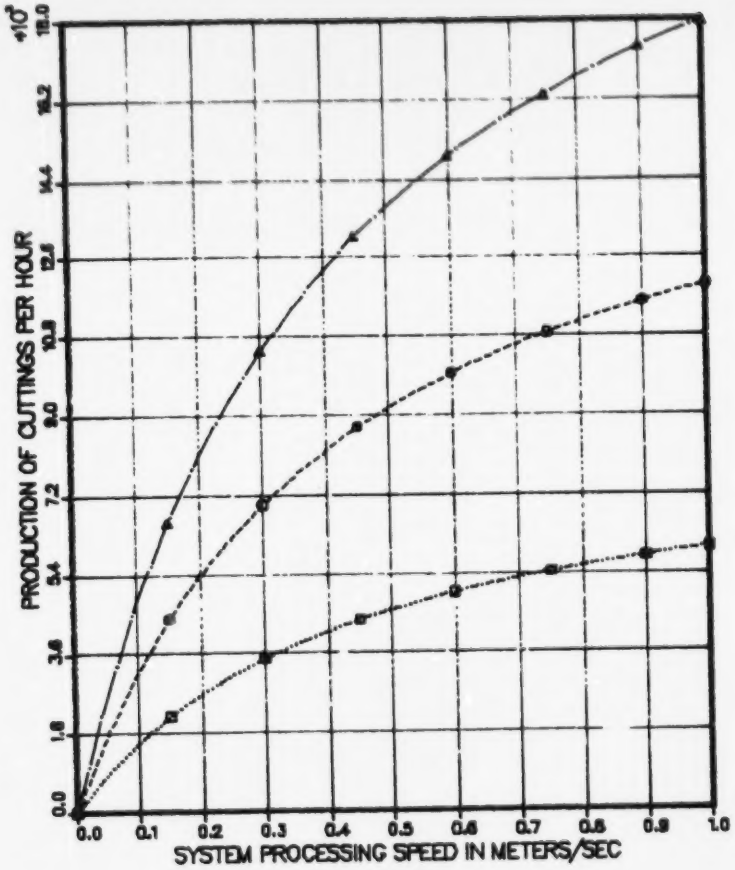
The productivity of the operation is computed in the following expressions.

$$CTW = \frac{WHL \times (1 - RJT/100)}{CTL/100}$$

where

CTW = number of cuttings per whip
WHL = average usable length of whips in metres
RTJ = production reject expressed in percent
CTL = length of cuttings in centimetres

$$WHR = \frac{3600}{WHL/SPD + DEP}$$



DELIMBING HEAD SPEED IS 1.00 METER /SEC–

WHIP PICKUP DELAY IS 5 SECONDS–

AVERAGE USABLE LENGTH OF WHIPS IS 2.20 METERS–

SCRAP PER WHIP IS 30.00 PERCENT–

LENGTH OF CUTTINGS IS 25 CENTIMETERS–

LEGEND

□ NUMBER OF DELIMBING HEADS IS 2 –

○ NUMBER OF DELIMBING HEADS IS 4 –

△ NUMBER OF DELIMBING HEADS IS 6 –

Figure 12. Productivity of an automatic system for production and storage of cuttings

where

WHR = number of whips produced per productive machine hour
WHL = average useable length of whips in metres
SPD = delimbing head speed in metres per second
DEP = whip pick-up delay in seconds

$$TWH = WHR \times NHD$$

where

TWH = number of whips processed per productive machine hour
NHD = number of processing heads

$$CHR = WHR \times CTW$$

where CHR = number of cuttings produced per productive machine hour per head.

$$TCH = CHR \times NHD$$

where TCH = total number of cuttings produced per hour.

In this analysis the productivity and the cost of the four-head machine is used, with a production of cuttings of approximately 12 000 cuttings/PMh. At the rate of 12 000 cuttings/PMh, and at an estimated 7 PMh/d, and 5 working days in a week, the system would produce 420 000 cuttings per week or approximately 1 260 000 cuttings in 3 weeks. In a 20-week period the plant would produce approximately 8 400 000 cuttings. If more cuttings are required, two shifts daily can be introduced, which would double the production of cuttings for given periods.

The list price of the service tractor is $33 600.00, and its maximum pto power is 45 kW. The allowance for the replacement tires is $0.58/PMh The tractor low and high price ranges are taken as $32 000.00 and $38 000.00.

The estimated cost of the automatic production machine for production, handling, and storing of cuttings is $278 000.00, which includes the cost of the loader. The low and high price ranges are $270 000.00 and $290 000.00, and the maximum power consumption is 40 kW/h.

The cost of the production of cuttings is shown in Fig. 13, with the labour accounting for 36.9% of the total cost of $248.45/PMh. The cost of capital is shown as $85.88, or 34.6% of the total cost.

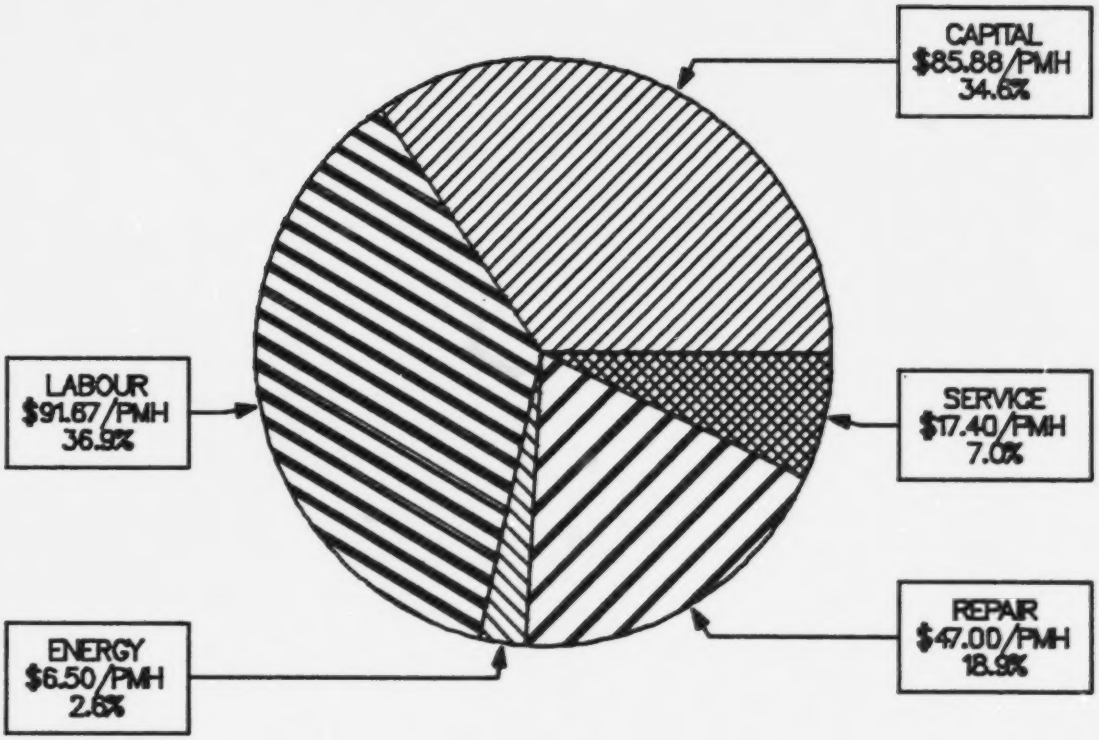


Fig. 13. The cost analysis of the production of cuttings. Total operational cost is $248.45 $/PMh

The total cost with adverse input conditions is $386.30, with the cost of capital accounting for 42.0% of the total, or $162.32, while the cost of labour remained almost the same. The cost of repairs at $99.83, or 25.8%, moved into second place after the cost of the capital.

The cost of the operation with adverse operational and financial inputs is $386.30, approximately 55% higher than the normal expected cost shown in Fig. 13.

PLANTING OPERATION - COST AND PRODUCTIVITY

The SRF planting operations are composed of two main mechanical subsystems: handling and transportation of magazines filled with cuttings and the planting operation itself.

Also, the planting function depends on the rotation period, because of the variation in the spacings between the trees within the rows and between the rows. For very wide spacings the number of planting heads on the automatic planting machine will be less than for a narrow spacing of a 2-year rotation plantation.

Productivity of planting operations depends on the ground speed, on the number of rows the planter plants simultaneously, and on the spacing between the rows planted, which is determined by the rotation period of the given plantation.

The productivity of the planting operation is computed by using the following expressions, which are similar to those used for computations of land preparation operations.

$$THP = \frac{SPD \times 1000}{LNG/WDT \times 10\ 000/LNG} \times WRW = \frac{SPD \times 1000}{10\ 000/WDT} \times WRW$$

where

THP = production of planting operation in hectares per productive machine hour
SPD = ground speed of the planting machine in kilometres per productive machine hour
LNG = length of planting rows in metres
WDT = row spacing in metres
WRW = number of rows planted simultaneously

$$DEL = \frac{TRN \times [(SPD \times 1000)/LNG]}{3600}$$

Where

DEL = delay per turn in a fraction of an hour
TRN = delay per turn in seconds

$$ADP = THP \times (1 - DEL)$$

where ADP = adjusted planting productivity in hectares per productive machine hour.

A typical productivity of automatic planting operations for 5-year rotation is shown in Fig. 14, illustrating the productivity of operations with automatic planting machines equipped with either two, four, or six planting heads. Under the given operational conditions, a 4-row planter will plant 1.19 ha of a 5-year rotation plantation per productive hour; also a 4-row planter will plant 0.79 ha of a 2-year rotation plantation and 2.27 ha of a 10-year rotation plantation. A 6-row planter will plant 1.7 ha/h of 5-year rotation and 1.14 ha of 2-year rotation plantation.

Handling and Transportation of Magazines

The support equipment needed to transport, handle, and load magazines on to the planter is illustrated in Fig. 1. A small tractor that pulls the

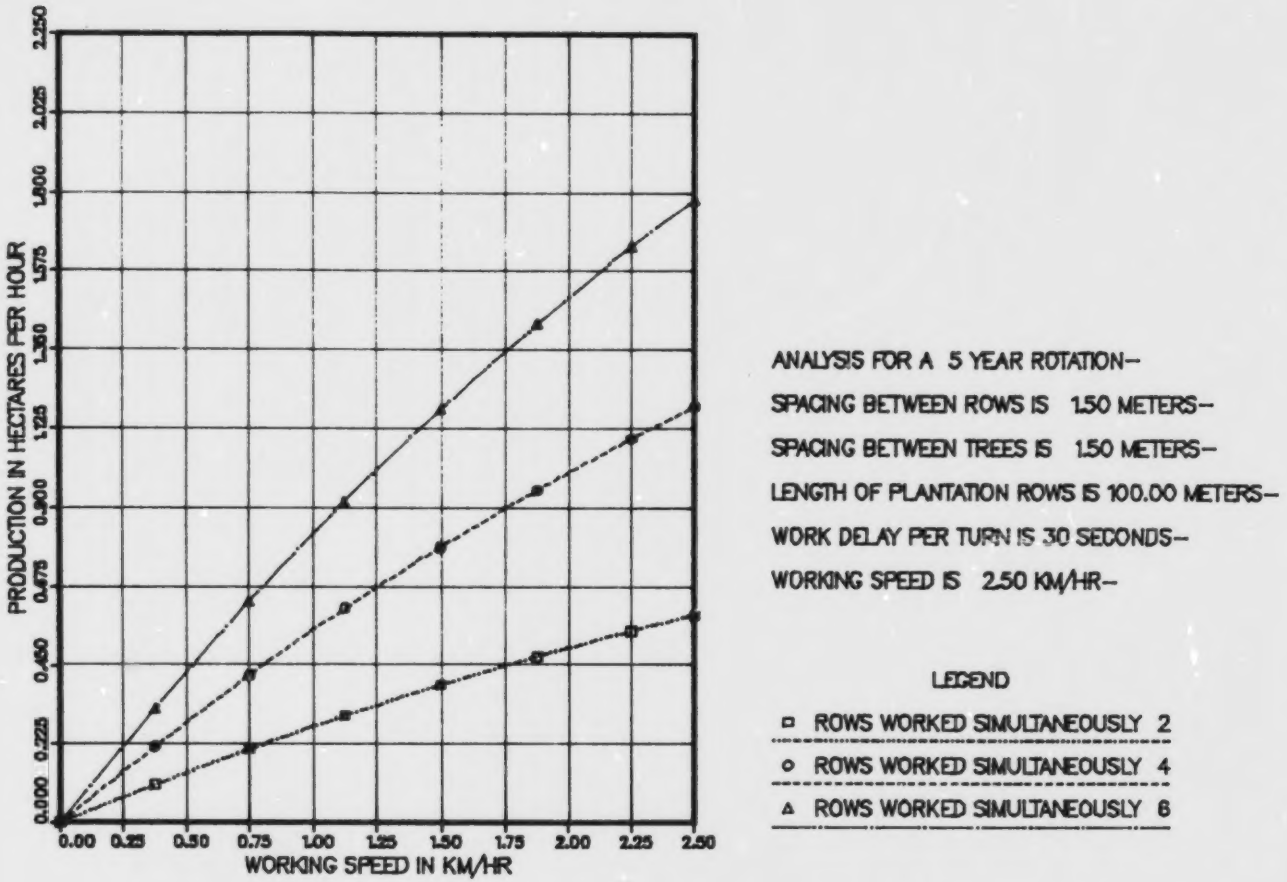


Figure 14. Analysis of planting productivity for a 5-year rotation plantation

field wagon loaded with magazines of cuttings is priced at $33 600.00, and it has a maximum pto power of 45 kW. The cost of replacement tires was estimated at $0.58/PMh.

The price of the loader is approximately $7 500.00, and the price of the field wagon is estimated at $10 000.00.

Planting

The planting machine is pulled by a large tractor, whose list price is estimated at $45 500.00, it has 63 kW of pto power, and the cost of the replacement tires is estimated at $0.75/PMh.

The estimated price for the 4-row planter is between $120 000.00 and $140 000.00; the 6-row planter is estimated to cost between $160 000.00 and $180 000.00.

Total Cost of Planting Operations

A total range of estimated prices for the operational tractors is $75 000.00 to $85 000.00 for both 4- and 6-row planting machines. The

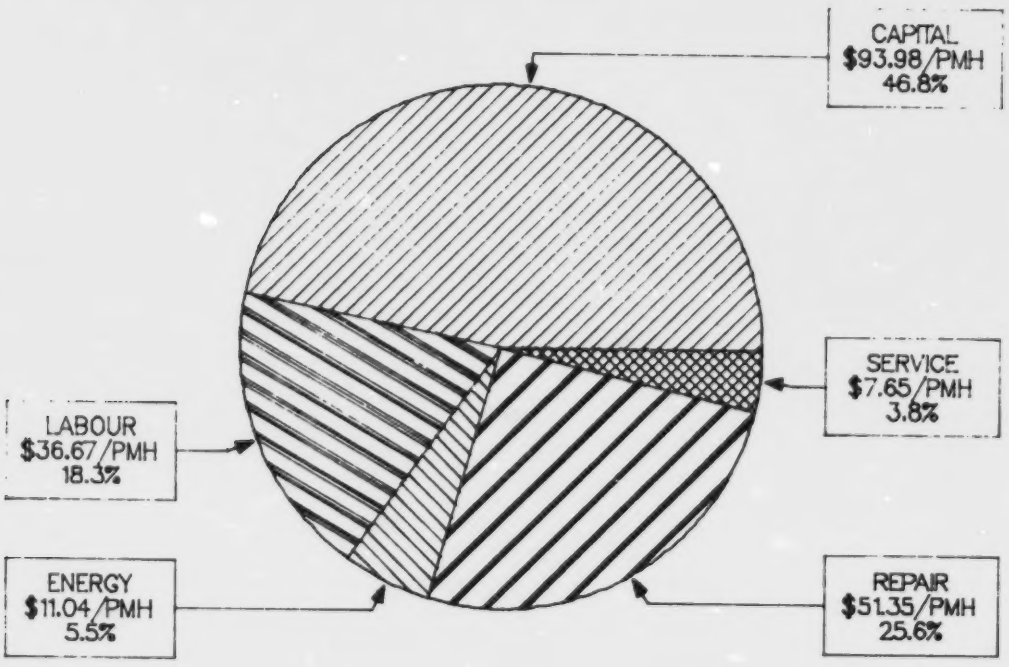


Figure 15. Analysis of planting costs for a 4-row planting system. Total operational cost is $200.70/PMh

ranges of prices for 4-row planting equipment, including the wagon and the loader, is between $149 000.00 and $160 000.00; for 6-row machines the range is $180 000.00 to $200 000.00.

The cost per hour of a 4-row planting system is illustrated in Fig. 15 and for a 6-row operation in Fig. 16.

Because of a relatively low labour input, the cost of capital and repair are the highest components of the total cost per productive hour. The upper range of cost per hour for the 4-row planting system is $269.76, or approximately 34% higher then the expected cost per hour shown in Fig. 1.

The total cost of the 4-row planting operation per hectare is a function of the rotation, namely the spacing between trees. For a 2-year rotation the productivity of a 4-row system is 0.79 ha/PMh; at an expected cost of $200.70/PMh, the cost per hectare is $200.70/0.79, which is $254.05; for the high cost of $269.76/PMh, the cost is $341.47/ha.

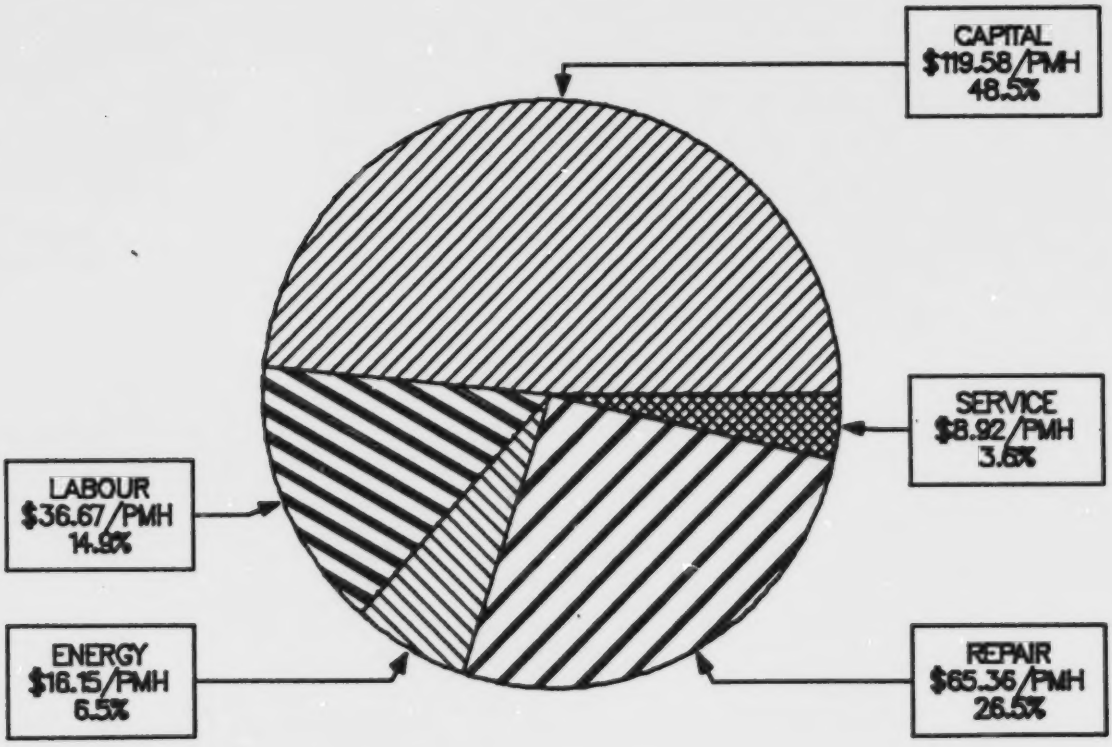


Figure 16. Analysis of planting costs for a 6-row planting system. Total operational cost is $246.88/PMh

The expected cost of the planting operation in a 10-year rotation plantation is $88.41/ha, and for the adverse conditions the cost is $118.84/ha. These costs are low because of a high productivity of 2.27 ha/PMh in a 10-year rotation plantation.

The 6-row planter in a 2-year rotation plantation will plant a hectare for $216.38, at expected costs per PMh, and $340.37/ha for more adverse operational and financial conditions. The same costs per hectare for a 5-year rotation plantation are $145.11 and $228.25.

The cost per hour of the 6-row planting operation illustrated in Fig. 16 is approximately 23% higher then the cost of the 4-row system shown in Fig. 15.

The difference of $45.96 between the two costs per hour shown in Fig. 15 and Fig. 16, when divided by four harvest periods becomes $11.49 per harvest. Assuming a yield of 50 ODt/ha, and an increase of 0.51 ha/PMh with a 6-row system, the cost per additional oven dry tonne of the increased area planted is approximately $0.45.

The total cost of planting operations with adverse operational and financial inputs for the 4- and 6-row systems are $269.76 and $388.02, which reflect the increase in the cost of capital and machine repair because of the higher discount and repair rates.

TENDING OPERATIONS - COST AND PRODUCTIVITY

Tending operation is either mechanical or chemical, depending on the desired means of controlling weeds. In this study, fertilizer application is also included in the tending operation, either on its own, or included with the mechanical tending operation.

Tending operations in 5- and 10-year rotation plantations are performed by single-row machines; because of the size of trees the machines cannot cover more than one row in one pass. The 2-year rotation plantation tending could cover several rows per pass in the first year of growth; however, the implement would require a high clearance capability to straddle the first year growth of hybrid poplars.

The productivity for single-row machines depends on the spacing between trees, on the ground speed of the machine, on the delay at turns, and on the length of rows.

The productivity of the tending operation is computed by using the same expressions as described under the computations of the planting

productivity. Basically, both operations are dependent on the spacings between the rows and between the trees, which makes it possible to vary rotations and the number of rows processed in one pass. However, tending of the 5- and 10-year rotation plantations is always done by a single-row machine, because of the tree sizes.

In a 5-year rotation plantation, at a ground speed of 2.5 km/h, the machine productivity is 0.3 ha/PMh, which was used in this analysis. The productivity analysis for a 5-year rotation plantation is shown in Fig. 17. All inputs for the 10-year rotation are the same as for the 5-year rotation, except for the spacing between the trees, which is 3 m, compared to 1.5 m for the 5-year rotation, which doubles the productivity to 0.59 ha/PMh.

Mechanical Weed Control

In all tending cost studies the list price of the tractor is $33 600.00, and it has a maximum pto power of 45 kW. The replacement cost for tires is $0.29 per operating hour. The price range for the tractor is between $34 000.00 and $40 000.00.

The price range for the cultivating implement is between $7 500.00 and $10 000.00.

The breakdown of the operational costs for one-pass mechanical tending only is shown in Fig. 18, with the labour cost of $18.33, or 52.5% of the total cost of $34.94. The cost per hectare is $116.46, for a productivity of 0.3 ha/PMh. The cost of capital is relatively small, because of a rather low capital input. If the expected cost inputs are replaced with adverse rates, the total cost becomes $48.58, or 14% higher than the cost in Fig. 18; the cost per hectare is $161.93.

When fertilizer is applied at the same time as the mechanical cultivation, the expected cost is $85.15/PMh and the more adverse cost is $98.11/PMh. The cost of fertilizer is $48.37/PMh. If applied to the productivity of 0.3 ha/h, these costs become $283.83/ha and $327.03/ha. The productivity of 0.3 ha/h applies to the 5-year rotation plantation.

Chemical Weed Control

The costs involved in the application of chemical weed control are similar to those in the application of fertilizer while cultivating between rows, with the addition of somewhat higher cost of the chemical treatment of $55.20/PMh, or $184.00/ha; also, an additional person was included in the application of chemicals, compared to only one operator when cultivating and applying fertilizer. The total expected cost per hour is $110.75,

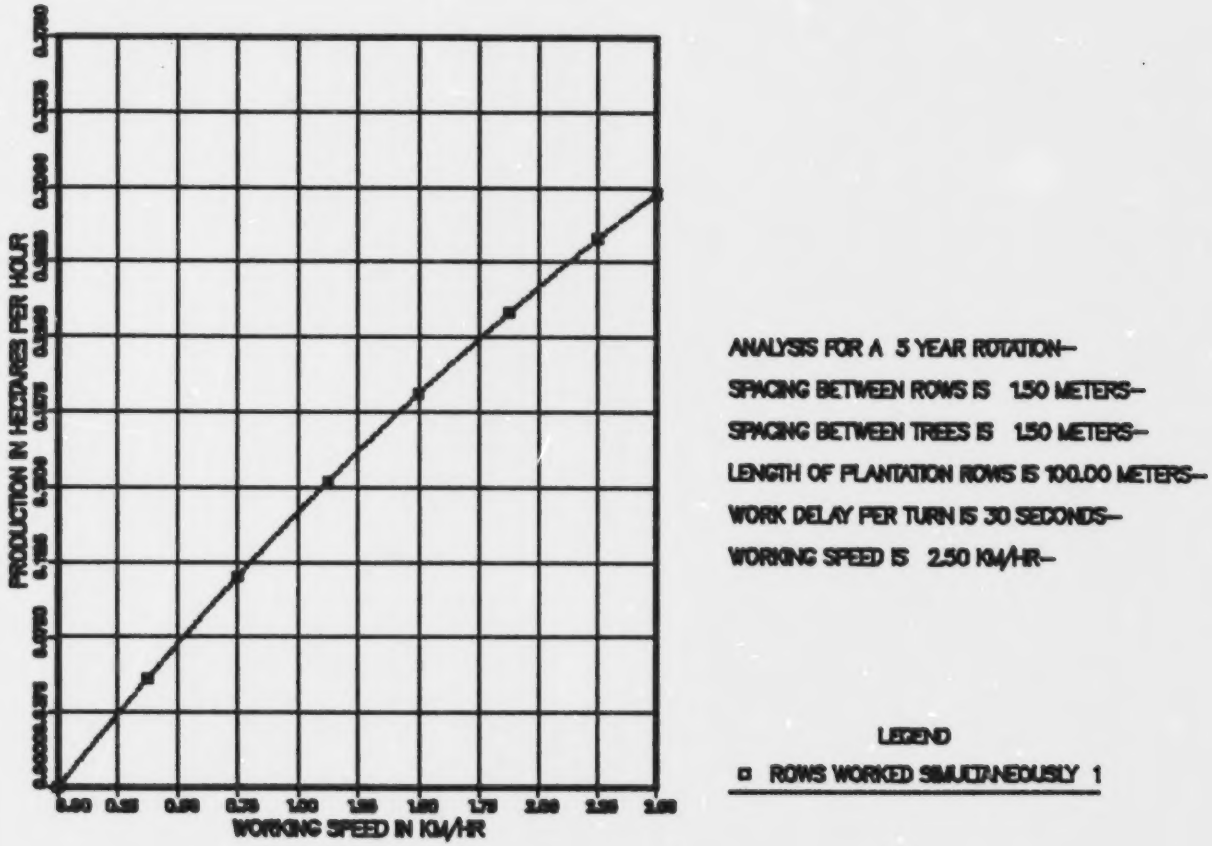

PRODUCTION IN HECTARES PER HOUR
WORKING SPEED IN KM/HR
ANALYSIS FOR A 5 YEAR ROTATION--
SPACING BETWEEN ROWS IS 1.50 METERS--
SPACING BETWEEN TREES IS 1.50 METERS--
LENGTH OF PLANTATION ROWS IS 100.00 METERS--
WORK DELAY PER TURN IS 30 SECONDS--
WORKING SPEED IS 2.50 KM/HR--
LEGEND
□ ROWS WORKED SIMULTANEOUSLY 1

Figure 17. Analysis of the tending productivity for a 5-year rotation plantation

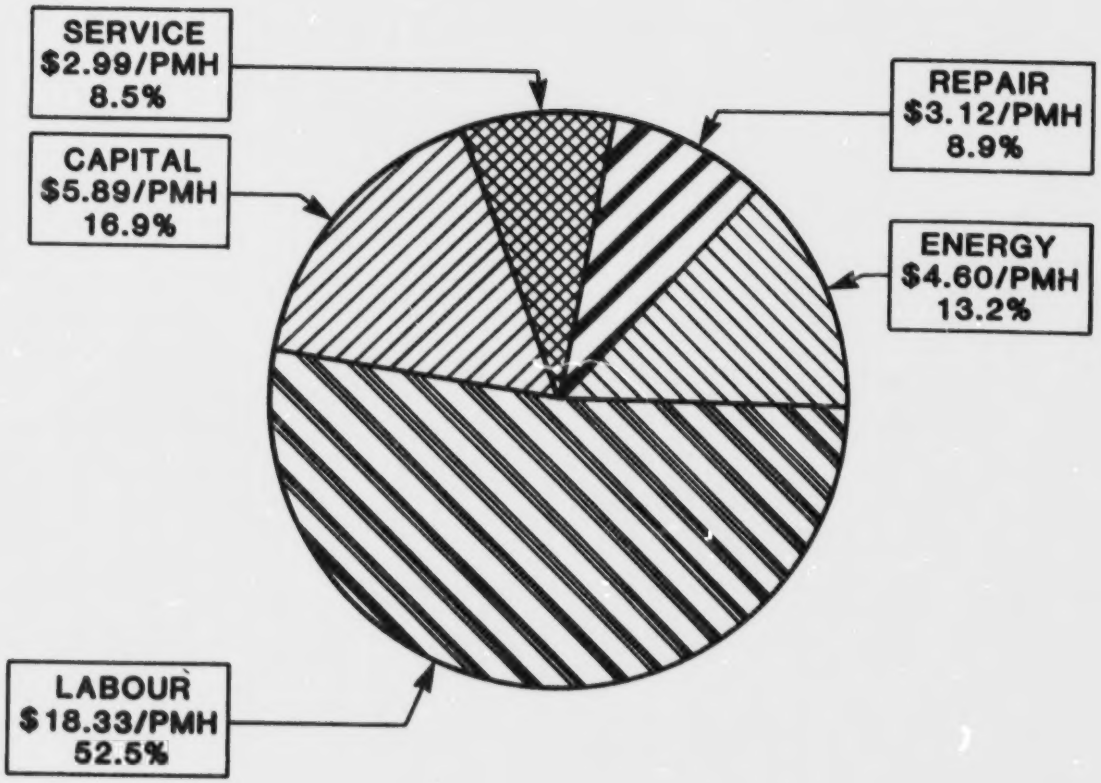


Figure 18. Cost analysis of the tending operation in a 5-year rotation plantation. Total operational cost is $34.94/PMh

or $369.16/ha. With adverse operational and financial inputs the cost is $119.74PMh, or $399.13/ha.

The tending costs for the 10-year rotation plantations are somewhat higher because of the greater area covered in 1 PMh, which requires double the amount of fertilizer and chemicals; however, the cost per hectare is proportionally reduced because of the higher productivity per hour. In a 10-year rotation plantation the cultivating and chemical application equipment covers 0.59 ha/h, because of the 3-m spacing between trees.

HARVESTING - COST AND PRODUCTIVITY

Harvesting operations are very complex, with many possible variations in operational and cost inputs; several reports discuss costs of hybrid poplar plantation harvesting;[1] Inman et al., 1977; McKenna, 1984; Curtin and Barnett, 1985). The interdependence of the biological productivity with the productivity of mechanical systems and their different operational cost criteria make for a considerable variation in reporting of costs. An attempt was made through sensitivity analysis to determine the optimum conditions in the combination of various harvesting attachments, their capability to harvest multiple numbers of rows, and the harvest support equipment. These questions were addressed under the four different types of plantations, including the variations in productivity.

Harvesting Small Dense Growth

In this analysis, when referring to small dense growth of hybrid poplar plantations, the study is applied to the spacing between trees of 0.3 m and 1 m between the rows. The rotation can be 2 to 3 years between harvests; however, in this analysis the rotation is assumed to be 2 years between harvests, and it is assumed that the plantation can produce five harvests from the same coppice.

The productivity is computed in oven dry tonnes per hour, which means the mechanical productivity is directly dependent on the biological productivity or on the average weight per tree harvested. Various combinations of equipment costs were studied in their relation to the weight of the biomass harvested per hour and per hectare.

The following expressions are used to compute productivity of harvesting operations for all plantation rotations. The variations are in the

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[1] Spanjer, D.L. 1982. Study and analysis of harvesting systems. David I. Spanjer & Associates, Toronto, Ontario. NRCC Int. Rep. Contr. No. OSX82-00119.

weights of trees and in the spacings between the rows and between the trees.

$$THW = \frac{(100/SPR + 100/SPT) \times WGH}{1000} \times RD$$

where

THW = theoretical biological productivity in oven dry tonnes per hectare
SPR = spacing between rows
SPT = spacing between trees in metres
WGT = average weight per tree in kilograms
RDC = reduction to obtain ODt, fraction of 100%

$$ADB = THB \times SRV$$

where

ADB = adjusted biological productivity in oven dry tonnes per hectare
SRV - estimated rate of tree survival, fraction of 100%

$$THP = \frac{SPD \times 1000}{LNG/SPR + 10\ 000/LNG} \times WRW = \frac{SPD \times 1000}{10\ 000/SPR} \times WRW$$

where

THP = theoretical machine production in hectares per productive machine hour
SPD = ground speed in kilometres per hour
LNG = length of rows in metres
SPR = spacing of rows in metres
WRW = number of rows worked simultaneously

$$DEL = \frac{TRN \times (SPD \times 1000)/LNG}{3600}$$

where

DEL = delay per turn in a fraction of an hour
TRN = delay per turn in seconds

$$ADP = THP \times (1 - DEL)$$

where

ADP = adjusted machine production in hectares per productive machine hour

$$PRD = ADB \times ADP$$

where

PRD = harvesting production in oven dry tonnes per productive machine hour

The productivity of the 4-row harvester is shown in Fig. 19. The weights of trees were derived from the projected productivity of 18 and 20 ODt/ha, with a rate of survival of 85%, with their respective weights of 1.27 and 1.41 kg per tree. Also, a possible increase of 20% with the application of the fertilizer is given as 1.52 and 1.69 kg per tree.

For 1.27 kg per tree, the productivity of a 4-row system at a ground speed of 2.5 km/h is 14.24 ODt/PMh, at a yield of 17.99 ODt/ha; for 1.41 kg per tree the productivity is 15.81 ODt/PMh at a yield of 19.97 ODt/ha; for 1.52 kg per tree the productivity is 17.05 ODt/PMh at a yield of 21.53/ha; for 1.69 kg per tree the productivity is 19.05 ODt/PMh at a yield of 23.95/ha.

The 4-row harvester for 2-year rotation plantations is expected to work in the first, single-stem plantation, as well as in the subsequent multi-stem coppice growth.

The list price of the harvesting tractor is $87 000.00, and the list price for the three forwarding tractors is $100 800.00 at the price of $33 600.00 each. The maximum pto power for the harvesting tractor is 185 kW, and for the three forwarding tractors it is 135 kW, for a total power of 320 kW. The range of prices used in the analysis is from $180 000.00 to $200 000,00. The cost of replacement tires is $1.12 per operating hour.

The estimated price of the harvesting attachment is $100 000.00, and for the three front-end piler attachments it is $45 000.00. The range of input prices for the equipment is from $140 000.00 to $150 000.00.

The expected cost per hour is shown in Fig. 20, with the labour component at 33.2% of the total and the capital at 28.8% of the total cost per hour.

In a plantation with a yield of 20 ODt/ha per harvest, with weight of 1.41 kg per tree, the expected cost of $220.64/PMh, if divided by the productivity of 15.81 ODt/PMh, gives the cost of $13.95/ODt. This is perhaps the best expected cost per oven dry tonne of the 2-year rotation plantation biomass. The cost is considerably higher than the cost for the 5-year and 10-year rotation plantations; the reason for the difference is a much lower biological productivity per hectare per harvest of the 2-year

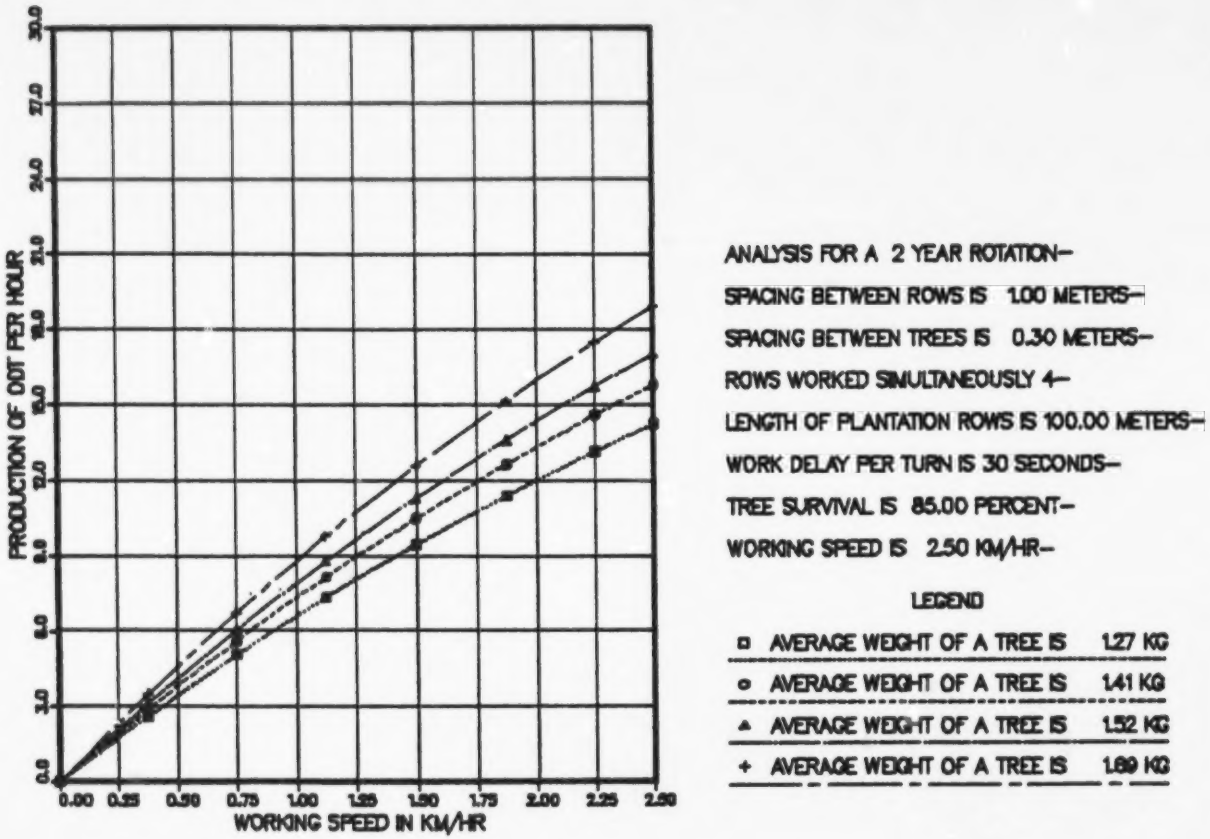
PRODUCTION OF ODT PER HOUR
WORKING SPEED IN KM/HR
0.00 0.25 0.50 0.75 1.00 1.25 1.50 1.75 2.00 2.25 2.50
ANALYSIS FOR A 2 YEAR ROTATION—
SPACING BETWEEN ROWS IS 1.00 METERS—
SPACING BETWEEN TREES IS 0.30 METERS—
ROWS WORKED SIMULTANEOUSLY 4—
LENGTH OF PLANTATION ROWS IS 100.00 METERS—
WORK DELAY PER TURN IS 30 SECONDS—
TREE SURVIVAL IS 85.00 PERCENT—
WORKING SPEED IS 2.50 KM/HR—
LEGEND
AVERAGE WEIGHT OF A TREE IS 1.27 KG
AVERAGE WEIGHT OF A TREE IS 1.41 KG
AVERAGE WEIGHT OF A TREE IS 1.52 KG
AVERAGE WEIGHT OF A TREE IS 1.69 KG

Figure 19. Productivity analysis of the 4-row harvesting operation in a 2-year rotation plantation

rotation plantation, while the costs of production remains substantially the same.

The cost per PMh of the system with 4-row harvester and three forwarders, having adverse operational and financial conditions, is $292.74, approximately 33% higher than the expected cost shown in Fig. 20.

The expected cost of the 2-row harvesting system, with two forwarders, is $138.36/PMh. In the plantation that will yield 20 ODt/ha; with the average tree weight of 1.41 kg, the system would produce 7.91 ODt/PMh. The estimated cost is $17.49/ODt.

The expected cost of the single-row harvesting system with two forwarders is $109.95/PMh. The above figures indicate a cost of $27.83/ODt for a single-row harvesting system.

The above analysis indicates the need for a multiple row operation; also, the 2-year rotation plantations may not be at present economically viable.

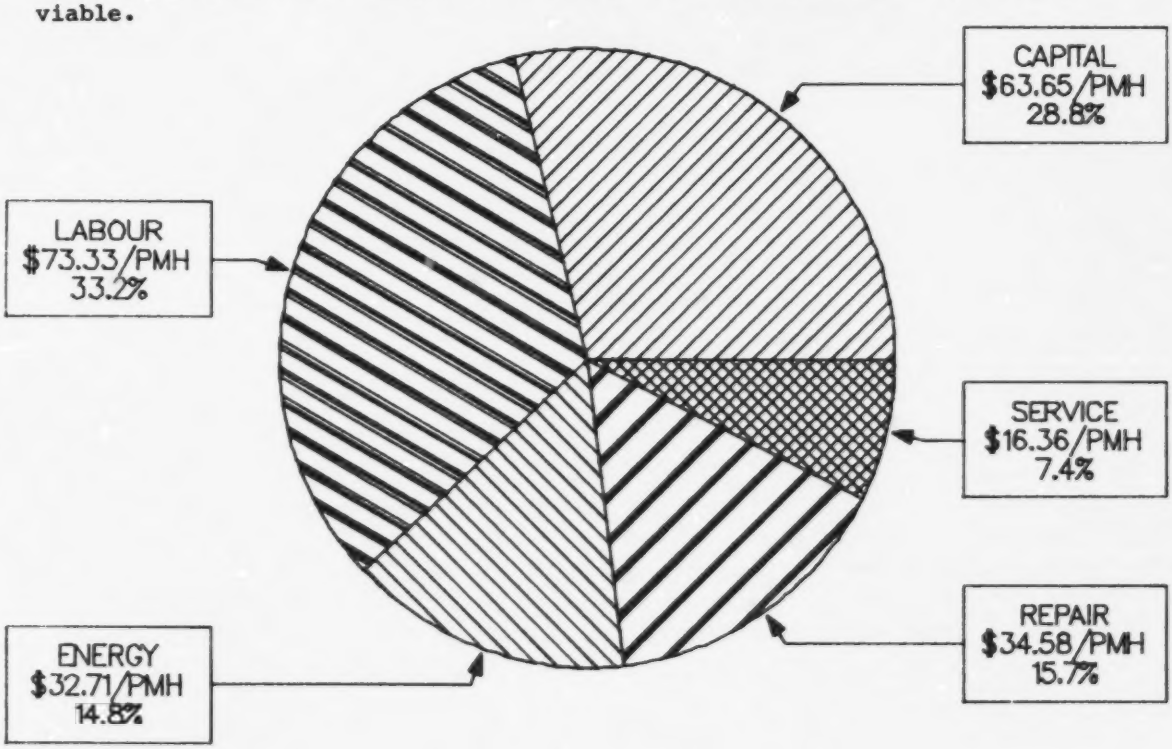

Fig. 20. Analysis of 4-row harvesting costs for a 2-year rotation plantation. Total operational cost is $220.64/PMh

Harvesting Small Single Trees

When referring to small single trees this study assumes the first growth of the 5-year rotation hybrid poplar plantation. A 4-row harvesting operation for 5-year rotation hybrid poplar plantations is illustrated in Fig. 5. The productivity of this system in a plantation having an average yield of 51 ODt/ha and an average tree weight of 27 kg is 60.56 ODt/PMh, or 1.19 ha/PMh. This productivity analysis is shown in Fig. 21.

The productivity of single-row and 2-row harvesting systems with similar conditions is decreased proportionally to 15.14 and 30.28 ODt/PMh.

The 4-row harvesting system in a 5-year rotation plantation with a yield approximately 20% higher then that shown in Fig. 21, or approximately 60.44 ODt/ha, for an average tree weight of 32 kg, will produce 71.78 ODt/PMh. The yield of 60.44 ODt/ha is expected in a plantation where fertilizer is applied once, possibly in the third year of growth.

The estimated list price for a harvester tractor is $210 000.00, and the price for five forwarding tractors is $227 500.00, at a list price of $45 500.00 per tractor. The maximum pto power of the harvester tractor is 114 kW, and the total pto power of five supporting tractors is 315 kW. The replacement cost of tires for the system is estimated at $16.80/PMh. The range of prices for the system is between $420 000.00 and $450 000.00.

The estimated price of the 4-row harvesting attachment is $130 000.00 and five front-end piler attachments are estimated at $50 000.00, or $10 000.00 per attachment. The cost of supplies for the attachments is estimated at $6.00 per operating hour. The range of equipment prices is from $170 000.00 to $190 000.00.

The total expected price for the operation is $347.75 per operating hour. At a productivity of 60.56 ODt/PMh, shown in Fig. 21, the cost is $5.74/ODt. In a plantation where fertilizer was applied, with a projected yield of 60.44 ODt/ha, and with a productivity of 71.78 ODt/PMh, the cost is $4.84/ODt. The expected cost analysis is shown in Fig. 22.

The adverse cost/PMh is $445.68, or $7.36/ODt, in a plantation yielding 51 ODt/ha, and $6.29/ODt in a plantation yielding 60.44 ODt/ha.

The expected cost per hour of an operational system with a 2-row harvester and five small forwarders is $231.61/PMh, or $7.65/ODt in a plantation yielding 51 ODt/ha; in a plantation yielding 60.44 ODt/ha the cost is $6.45/ODt. The adverse cost of the harvesting operation is $318.61/PMh.

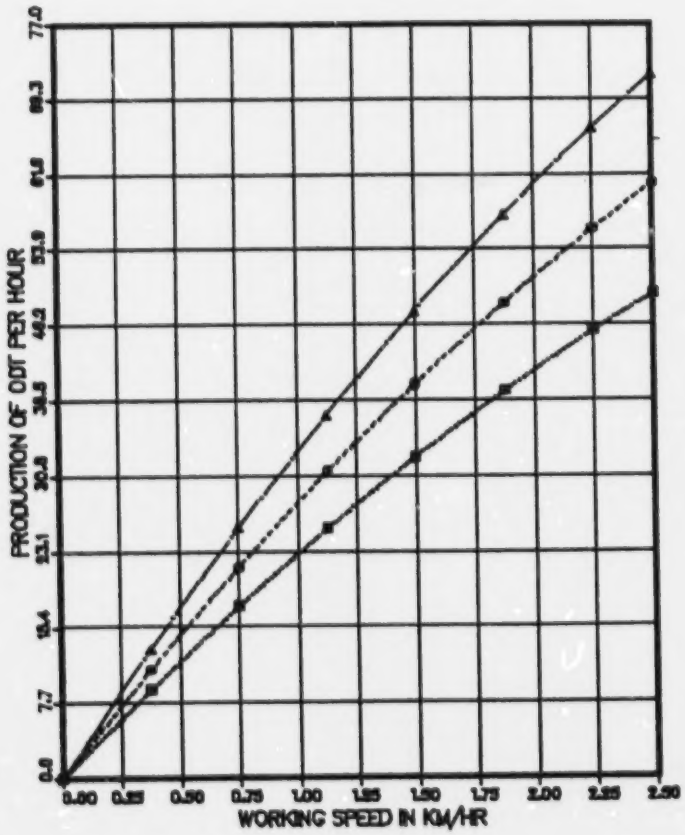

Figure 21. Analysis of the 4-row harvesting productivity in a 5-year rotation plantation

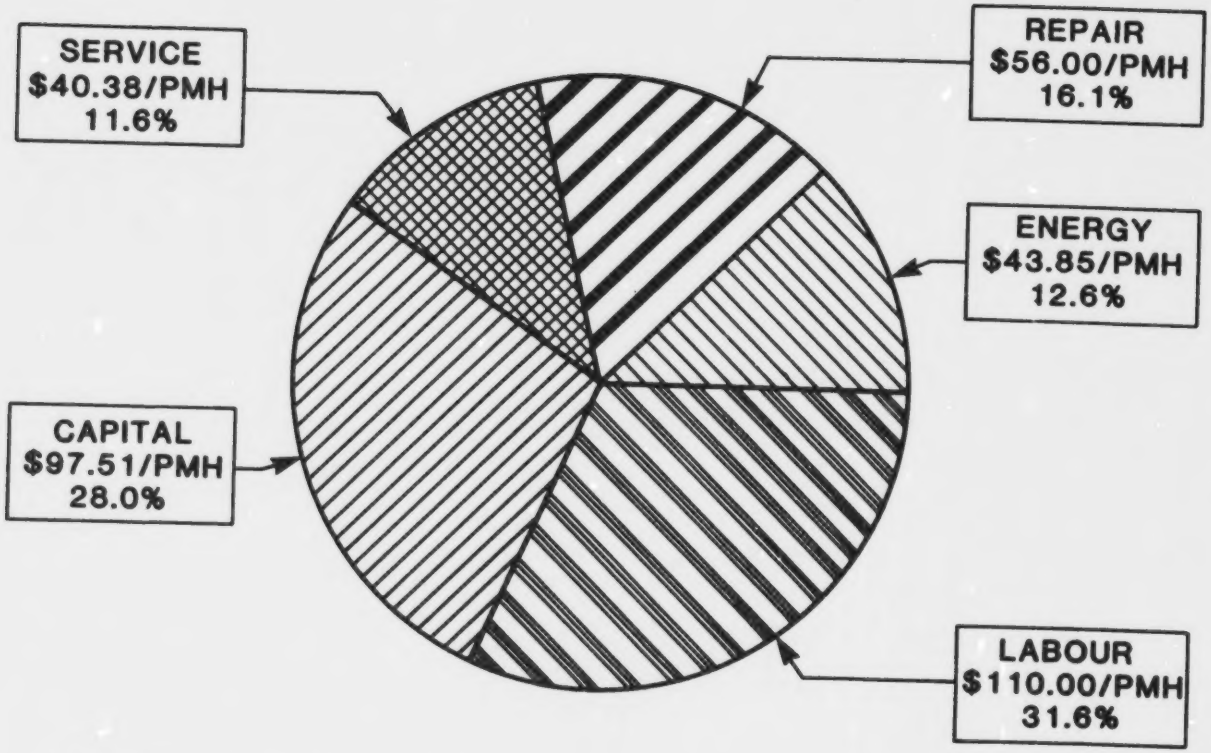

Figure 22. Analysis of harvesting costs for a 4-row harvesting system in a 5-year rotation plantation. Total operational cost is $347.75/PMh

The expected cost of a single row harvesting operation with three small forwarders is $159.32/PMh, for a cost per oven dry tonne of $10.52, or $8.88 in a plantation yielding 60.44 ODt/ha. The adverse cost of the operation is $204.76/PMh.

Harvesting Large Single Trees

The large single trees in this study are the trees of the first growth of a 10-year rotation hybrid poplar plantation. The productivity of a 2-row harvesting system, in a plantation of an expected yield of 64.22 ODt/ha, with an average tree weight of 136 kg, is 76.26 ODt/PMh, or 1.19 ha/PMh. In a plantation of an average tree weight of 132 kg, and a yield of 62.33 ODt/ha, the productivity is 74.02 ODt/PMh. The productivity analysis is shown in Fig. 23. In a plantation with an average tree weight of 140 kg, and a yield of 66.11 ODt/ha, the expected productivity is 39.25 ODt/PMh.

The cost of a 2-row harvesting system is based on the list price of the harvester tractor of $210 000.00, and on the cost of three medium-sized commercial skidders for a total list price of $270 000.00, at a price per skidder of $90 000.00. The skidders are assumed to be used on other wood-lot harvesting operations through the year. The total estimated price range for all tractors is from $470 000.00 to $490 000.00. The maximum pto of the harvester tractor is 114 kW, and the pto power for the three skidders is 245 kW.

An estimated price range of the harvester attachment is between $100 000.00 and $120 000.00.

The expected cost of the 2-row harvesting system is $280.21 per operating hour. In a plantation with a yield of 64.22 ODt/ha per harvest and an average weight of tree of 136 kg, the cost is $3.67/ODt. The analysis of the expected total cost for the 2-row harvesting system is shown in Fig. 24. In a plantation yielding 62.33 ODt/ha with an average tree weight of 132 kg, the cost is estimated at $3.70/ODt. In a plantation yielding 66.11 ODt/ha, and an average tree weight of 140 kg, the projected cost is $3.57/ODt.

The adverse cost per productive hour of a 2-row harvesting system is $351.54; the cost per oven dry tonne is $4.61 in a plantation of an average yield of 64.22 ODt/ha, with an average tree weight of 136 kg.

The cost of a single-row harvesting system is based on an operation with two medium-sized commercial skidders priced at $90 000.00 each and the harvester priced at $210 000.00, for a total range of tractor prices of

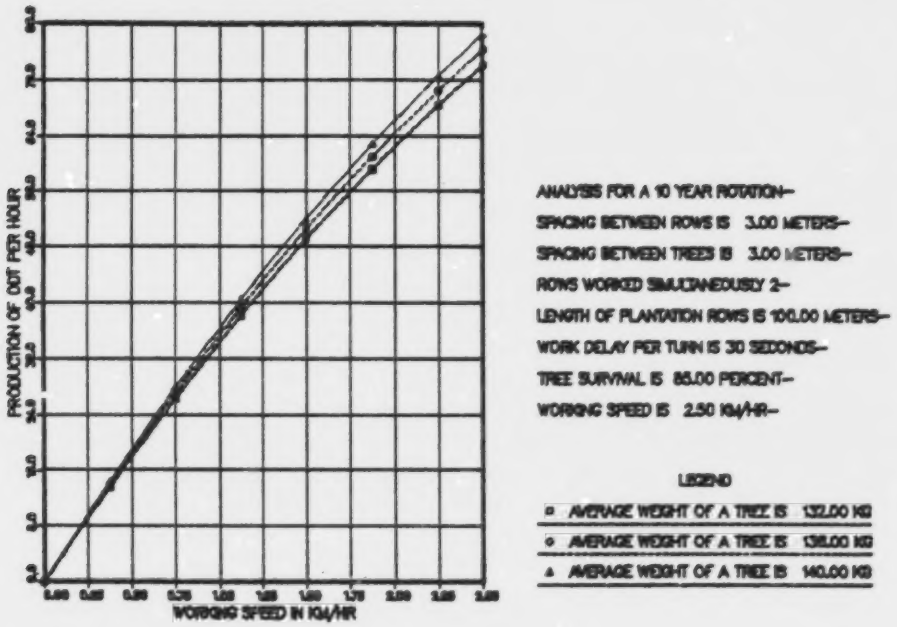
PRODUCTION OF ODT PER HOUR
WORKING SPEED IN KM/HR
ANALYSIS FOR A 10 YEAR ROTATION-
SPACING BETWEEN ROWS IS 3.00 METERS-
SPACING BETWEEN TREES IS 3.00 METERS-
ROWS WORKED SIMULTANEOUSLY 2-
LENGTH OF PLANTATION ROWS IS 100.00 METERS-
WORK DELAY PER TURN IS 30 SECONDS-
TREE SURVIVAL IS 85.00 PERCENT-
WORKING SPEED IS 2.50 KM/HR-
LEGEND
AVERAGE WEIGHT OF A TREE IS 132.00 KG
AVERAGE WEIGHT OF A TREE IS 136.00 KG
AVERAGE WEIGHT OF A TREE IS 140.00 KG

Fig. 23. Analysis of the productivity of a 2-row harvesting system in a 10-year rotation plantation

$380 000.00 to $400 000.00 and a total maximum pto power of 277 kW. The cost of replacement tires is estimated at $14.00/PMh.

The total cost per machine hour of the single row harvesting system is $209.14, and for adverse cost inputs the cost is $258.47/PMh. The low cost is $5.48/ODt in a plantation with a yield of 64.22 ODt/ha, and $6.79/ODt for the high cost per hour.

Harvesting Coppice

There is not enough information on the growth of 5- and 10-year rotation after the first harvest. The indications are that only one to three stems remain after the year 5, and only 1 stem at year 10 (Gordon and Voss, 1984). Harveting of multi-stem growth would require a harvesting attachment different than that for the first single-stem harvest, shown in Figs. 5 and 6.

The productivity per hectare is expected to increase as the root system develops; however, the mortality of trees will increase, therefore in this analysis the productivity per hectare is assumed to remain at the level of the first harvest, for 5- and 10-year rotation plantations.

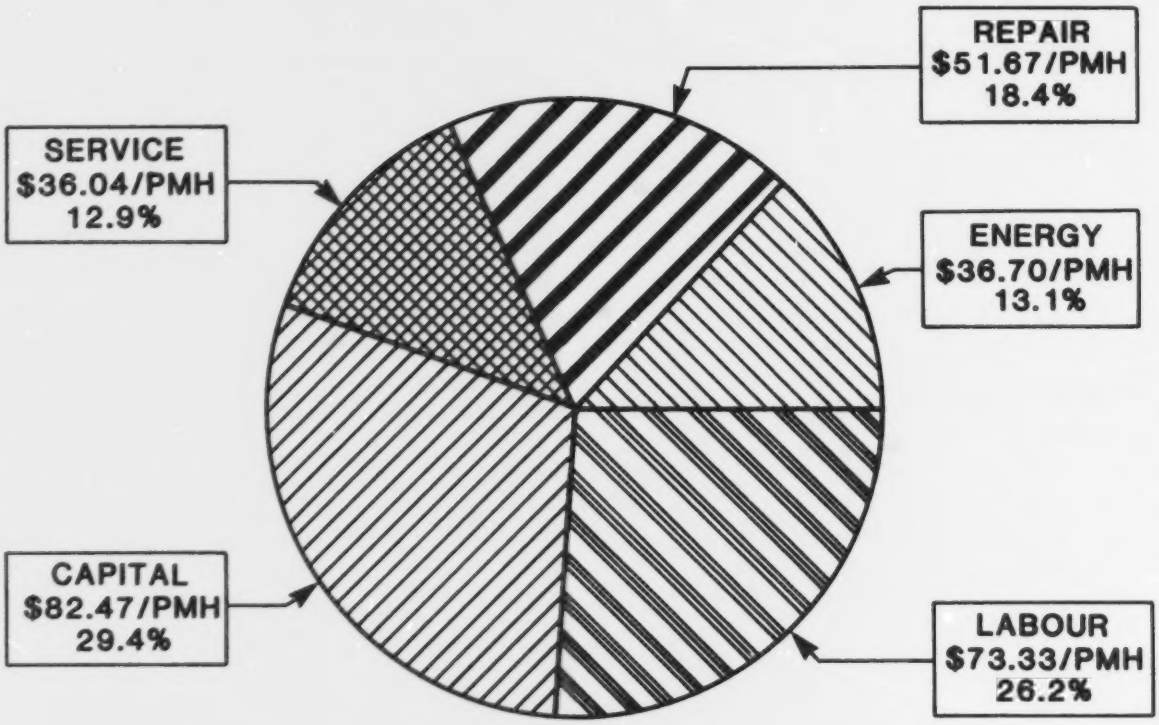

Fig. 24. Cost analysis of the 2-row harvesting system in a 10-year rotation hybrid poplar plantation. Total operational cost is $280.21/PMh

The costs of harvesting attachments and support equipment can be assumed to remain similar to those outlined for 5- and 10-year rotation, single stem plantations. Also, the harvester attachment for more than a single row of trees is technically feasible within the costs outlined for the single stem equipment.

CHIPPING - COST AND PRODUCTIVITY

Productivity

The productivity of a chipping operation is difficult to compute because many variables affect the productivity of the system. This analysis depends on the accuracy of the estimates of feeding efficiency and the delay in moving vans from and to the chipper. The following expression is used to compute the productivity of the chipping system.

$$PRD = TEO \times (1 - DEL) \times EFF \times RDC$$

where

PRD = production in oven dry tonnes per productive machine hour
TEO = given theoretical productivity of the chipper
DEL = moving delay in a fraction of an hour
EFF = estimated chipper feeding efficiency
RDC = percent weight loss to one oven dry tonne

In this analysis the theoretical productivity was assumed to be 100 green tonnes per hour, the feeding efficiency is estimated at 60%, and the delay due to moving trailers is estimated as 7 min/h, or approximately 11.6%, making the available time 88.4% of an hour, caused by delays. The required weight reduction for oven dry biomass is assumed to be 50%. The analysis of productivity is shown in Fig. 25.

Using these inputs the productivity of the chipping operation is 26.5 ODt/PMh.

Cost

The cost inputs for the operation are based on the system with a mobile self-propelled chipper and a support tractor for handling chip vans to and from the chipper. The list price of the 100-t chipper is given as $251 000.00, and the available power is 485 kW. The range of prices in the input is $250 000.00 to $270 000.00. Supplies are estimated as $2.00/PMh for the expected cost input, and $4.00/PMh for the adverse cost input.

The list price of the support tractor is $45 500.00, and the pto power is 62 kW. The cost of replacement tires is estimated at $0.75/PMh.

The total expected cost of the chipping system is shown in Fig. 26.

The total expected cost of the system is $190.29/PMh, or $7.18/ODt for the estimated productivity of 26.5 ODt per operating hour.

The cost of the operation with adverse operational and financial inputs is $248.49/PMh, for a cost of $9.38/ODt.

TRANSPORTATION - COST AND PRODUCTIVITY

The analysis of the transportation system is presented in a basic form; the cost is treated similarly to the cost of other operations, with highway tractors and semi-trailers as component inputs. The productivity projects the productivity of the whole system, assuming a sufficient number of spare trailers at the landing to eliminate a possible delay caused by the loading of the trailer.

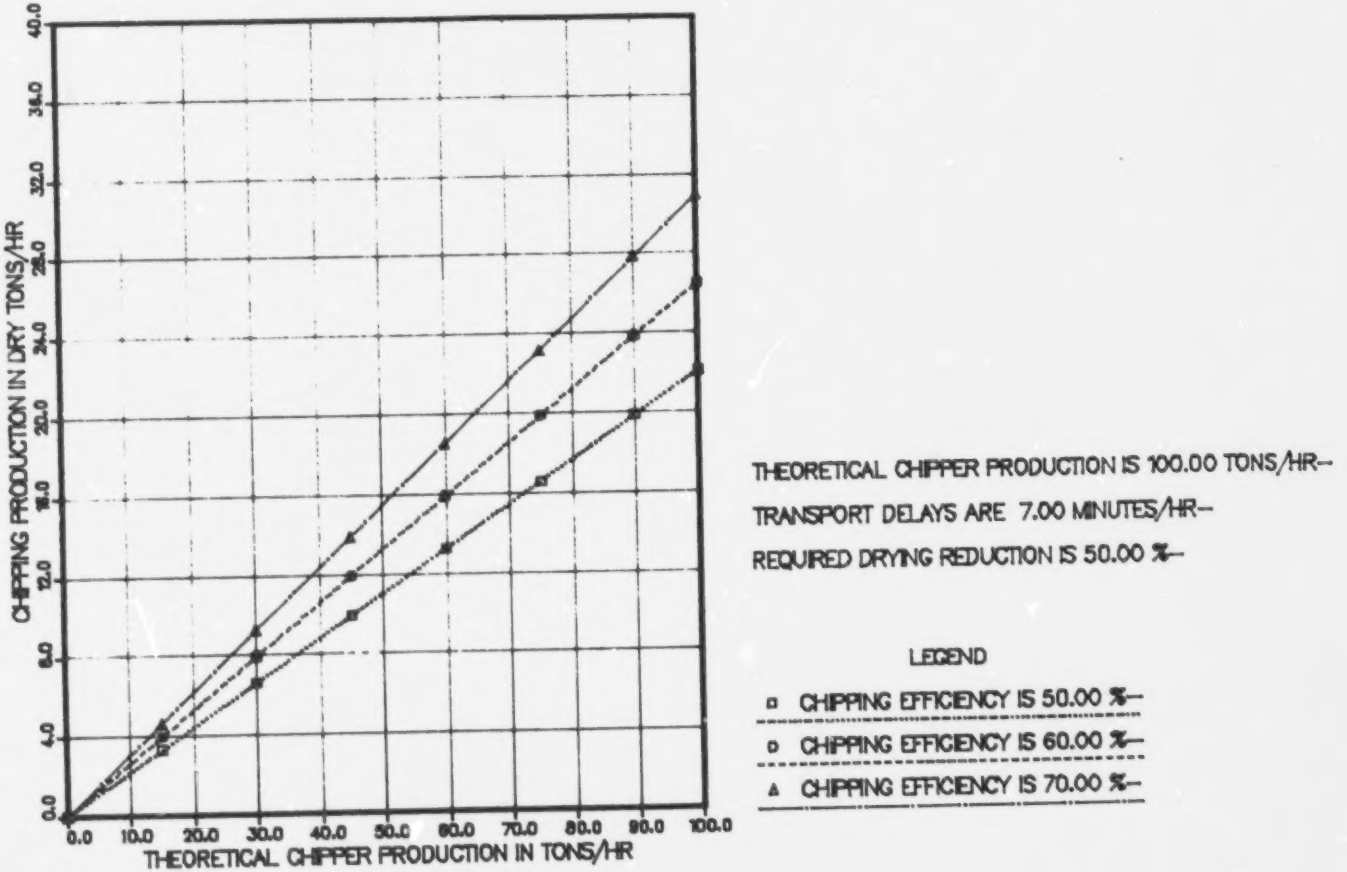

Figure 25. Analysis of chipping productivity

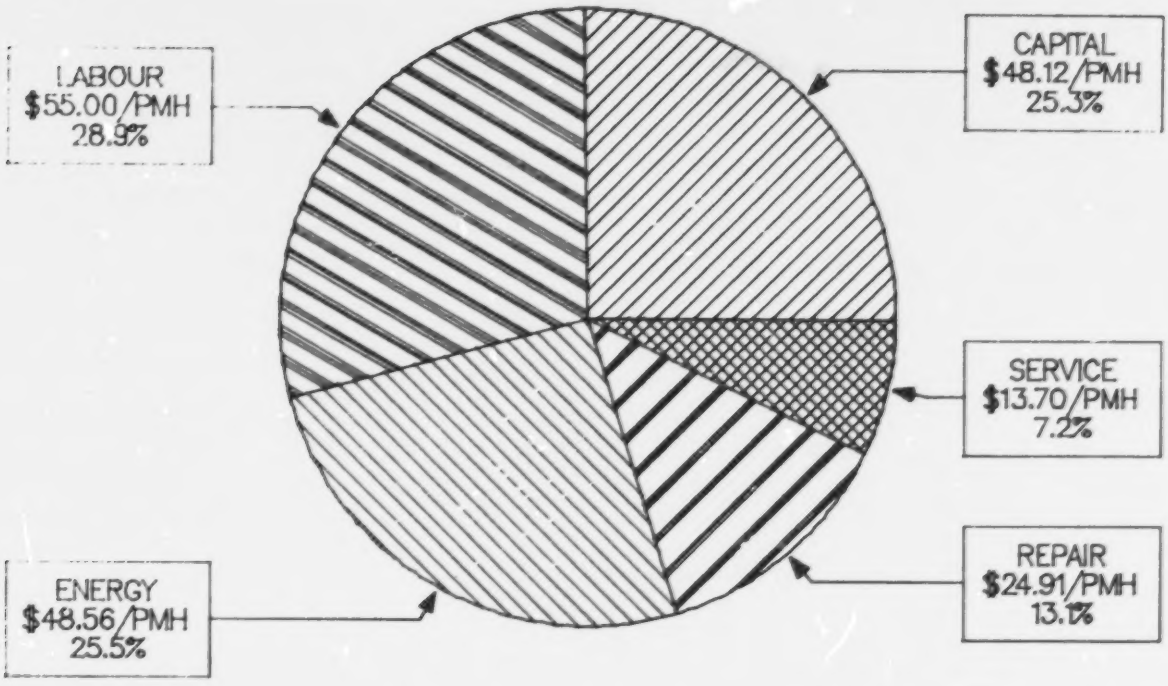

Figure 26. Cost analysis of the chipping operation. Total operational cost is $190.29/PMh

Productivity

The productivity was computed by calculating production in dry tonnes for 5% intervals between the low and the high vehicle speed, for the most likely average distances from plantation to the conversion point. In this analysis the average distance is considered to be 30 km, and the average road speed is 70 km/h. The base expression in the analysis is the equation for the computation of the single vehicle cycle time.

$$VCL = LDE + TRS + UDE + RTN$$

where

VCL = single vehicle cycle time in minutes
LDE = landing delay in minutes
TRS = transport time in minutes
UDE = unloading delay in minutes
RTN = return time in minutes - considered equal to delivery time

The number of loads per vehicle were computed by dividing the total estimated production time per day by the single vehicle cycle time. The load per vehicle is then multiplied by the number of loads per vehicle, and

the result is multiplied by the number of road vehicles in the system, giving the total production in tonnes for the system. The dry tonnes are obtained by multiplying the total production by the reduction factor, which is assumed to be 50%.

In this study the productivity was taken at the average distance of 30 km to conversion point and the average road speed of 70 km/h. The analysis of the productivity of the transportation system is shown in Fig. 27. At that speed and distance the productivity of the system is 41.48 ODt/PMh. The single vehicle cycle time is 69.43 min, and the total number of loads for all vehicles are 16.85, making a total of 539.26 green tonnes of biomass. The number of productive hours is estimated at 6.5.

Cost

The estimated list price for the highway tractors is $80,000.00 per tractor, and the range for the three tractors is $240,000.00 to $270,000.00, with a total power of 783 kW. The tire replacement cost is $4.5/PMh.

The estimated cost for the chip semi-trailer is $42,000.00, and the range for five trailers in the system is from $200,000.00 to $270,000.00. The estimated cost of tire replacement is $12.00 per operating hour. The cost analysis of the transportation system is shown in Fig. 28.

The total expected cost is $237.67 per operating hour, or $5.73/ODt, for the system capable of delivering 41.48 ODt/PMh. The system is assumed to have two spare semi-trailers at the chipping point, so that trailers are loaded and made ready for the tractors to take them to the conversion point, with the least delay at the landing.

The cost based on the adverse inputs is $300.32 per operating hour, or $7.24/ODt delivered to the conversion point.

EQUIPMENT TRANSPORTATION - COST AND PRODUCTIVITY

The equipment transport costs are added to the final computation of the total SRF operations costs per oven dry tonne, by adding the prorated cost for transport to the cost per hour for each operation. The productivity is computed for each operation separately, because of the different numbers of equipment transported for a particular operation and because of varying distances to the operation site.

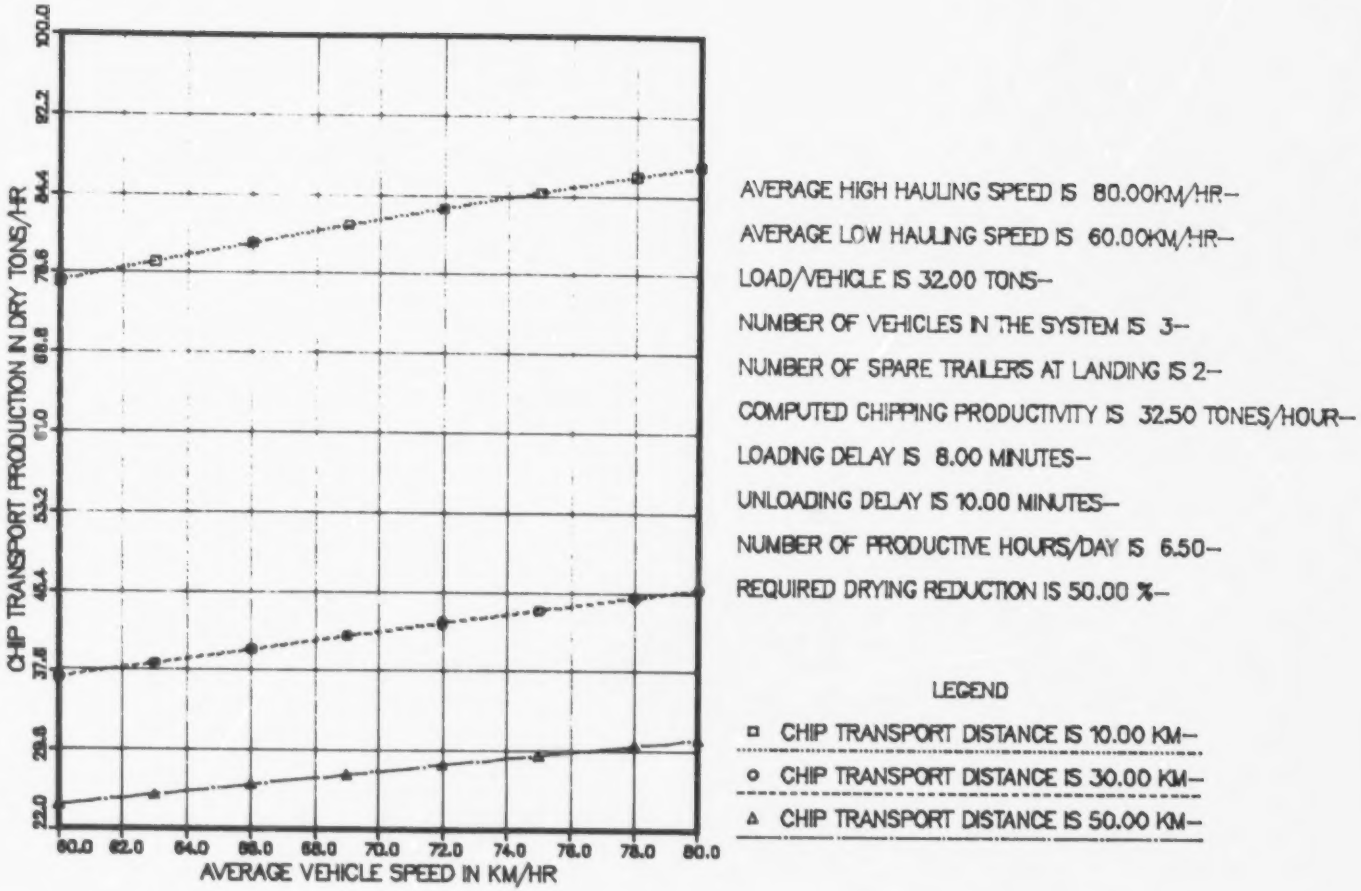
CHIP TRANSPORT PRODUCTION IN DRY TONS/HR
100.0
92.2
84.4
76.6
68.8
61.0
53.2
45.4
37.8
29.8
22.0
60.0 62.0 64.0 66.0 68.0 70.0 72.0 74.0 76.0 78.0 80.0
AVERAGE VEHICLE SPEED IN KM/HR
AVERAGE HIGH HAULING SPEED IS 80.00KM/HR--
AVERAGE LOW HAULING SPEED IS 60.00KM/HR--
LOAD/VEHICLE IS 32.00 TONS--
NUMBER OF VEHICLES IN THE SYSTEM IS 3--
NUMBER OF SPARE TRAILERS AT LANDING IS 2--
COMPUTED CHIPPING PRODUCTIVITY IS 32.50 TONES/HOUR--
LOADING DELAY IS 8.00 MINUTES--
UNLOADING DELAY IS 10.00 MINUTES--
NUMBER OF PRODUCTIVE HOURS/DAY IS 6.50--
REQUIRED DRYING REDUCTION IS 50.00 %--
LEGEND
CHIP TRANSPORT DISTANCE IS 10.00 KM--
CHIP TRANSPORT DISTANCE IS 30.00 KM--
CHIP TRANSPORT DISTANCE IS 50.00 KM--

Figure 27. Analysis of the chip transport productivity for 6.5 productive hours out of an 8 h shift

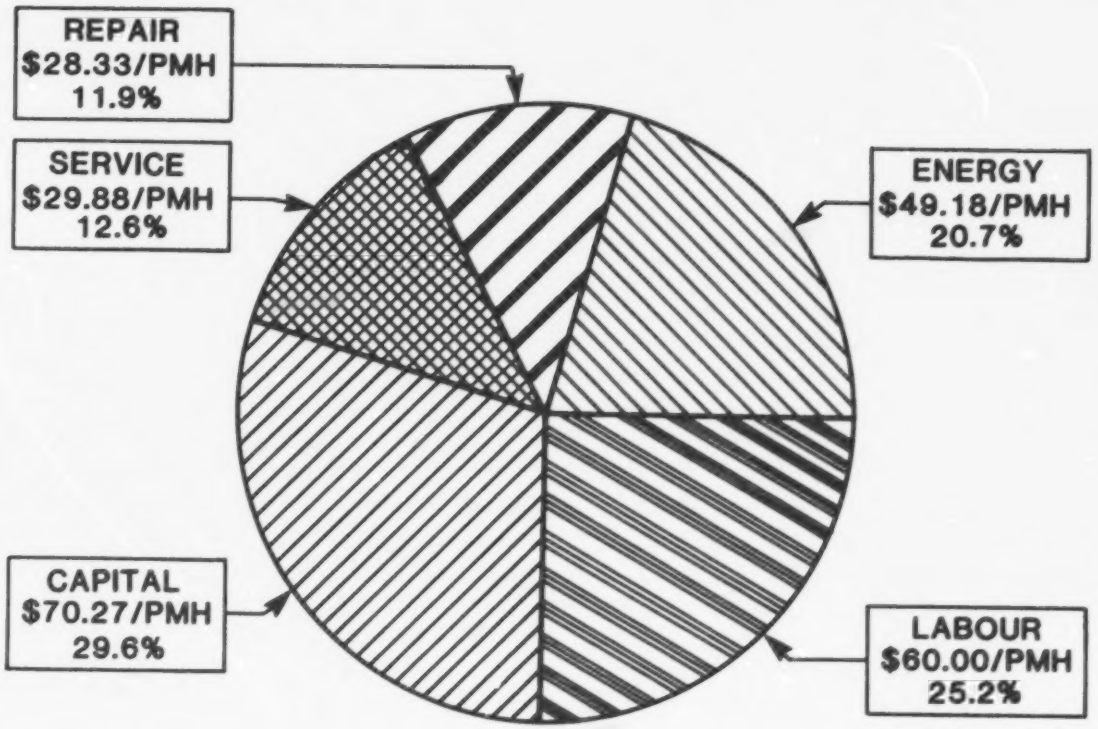

Fig. 28. Analysis of chip transportation costs. Total operational cost is $237.67/PMh

Productivity

The productivity of the equipment transport system is computed for each operation based on the number of tractors and equipment needed to be transported to the site of the operation. The distance can vary depending on the assumption of the interaction of various operations. The distance and the average speed of 70 km/h provide the time interval required to take machines to the site and to return the transport equipment to the starting point.

The total time, including travel and delays, is divided by an estimate of the number of hours the operation will take place, based on an estimate of the number of hectares to be covered and on the productivity of the operational system in hectares per hour.

The number of trips the transport will make depends on the number of machines that must be transported, as for instance in the case of the land preparation operation, the number of transport trips is estimated as three, so the cost for the transport will be equivalent to three return trips.

Cost

The list price range of the equipment transport tractor is estimated as $75 000.00 to $85 000.00, and the maximum available power is assumed to be 224 kW. The cost of replacement tires is estimated at $1.5 per operating hour.

The price range of the equipment transport semi-trailer is estimated as $25 000.00 to $35 000.00, and the cost of the replacement tires is $0.96/PMh.

The total expected cost of the transport operation is $69.81 per operating transport hour, and the total high cost per operating transport hour is $106.87.

To simplify the computations of the operational costs, corrected for the transport of the equipment, the size of the plantation is assumed to be 20 ha for all plantation operations. Also, the unloading and loading delays are taken as 30 min each, 1 h per transport trip. The average distance to the plantation is taken as 30 km, and the average road speed is 70 km/h. The total time of travel and delays is 1.857 h, which amounts to $129.64 for the expected cost of one equipment transport trip and $198.46 for the trip at the high cost inputs. The cost analysis of the equipment transport operation is shown in Fig. 29.

The cost of the equipment transportation operation with high cost inputs is $106.87, or $5.34 for each hour of the operation, assuming 20 h of work at the given site.

COST PER OVEN DRY TONNE

The final cost analysis of short rotation forest operations is done by computing cost per oven dry tonne for all seven operations. The cost per hour for each operation is converted into the cost per oven dry tonne.

Costs of harvesting, chipping, and transport of chips to the processing point are directly related to their own productivity only; the costs of these operations are converted directly to costs per oven dry tonne.

Tending and fertilizer application are done in the years between planting and harvesting and are directly applicable to the next harvest only; therefore, the cost of the tending operation is compounded for the number of years to the harvest of that particular crop of trees.

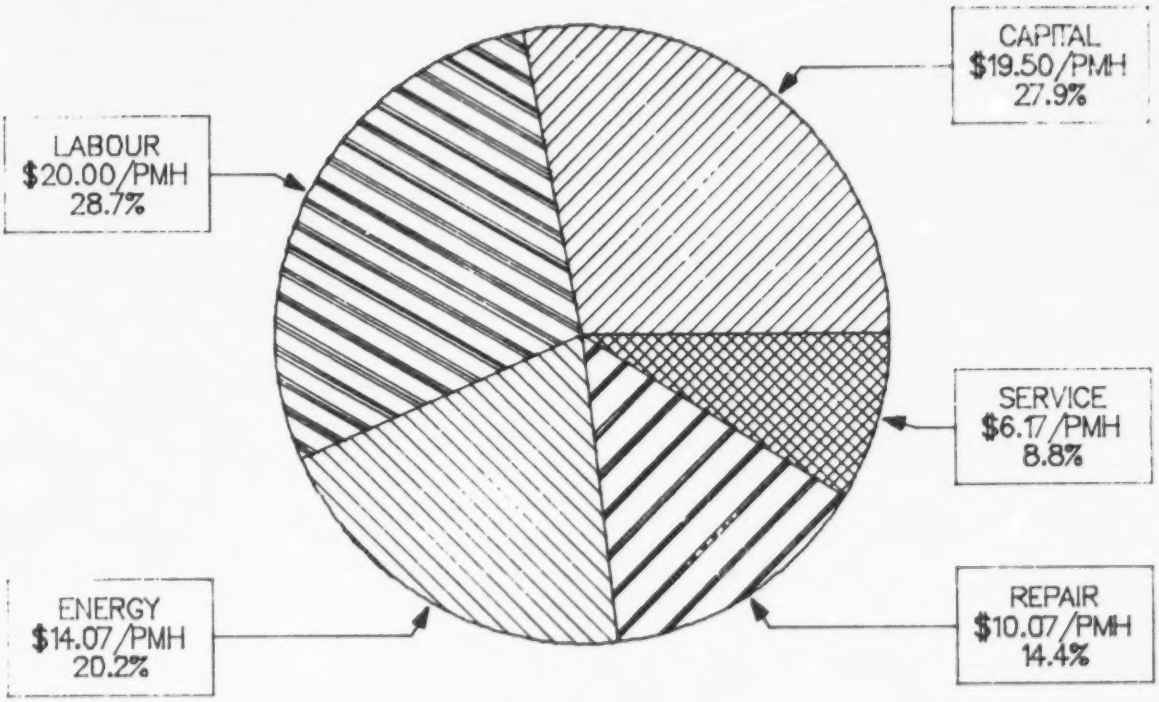

Figure 29. Analysis of the equipment transportation costs. Total operational cost is $69.81/PMh

The costs per oven dry tonne for all basic operations required to establish plantations are spread over several rotations and must reflect an average cost per oven dry tonne computed for all harvests. These operations are land preparation, nursery operations including whip production and harvesting, and planting. In this analysis the computation of the average cost per oven dry tonne is based on the premise that a cost, or price per oven dry tonne, can be established in dollars of the base year, which when applied to the periodic harvests will result in a total income equal to the total stream of investment, reflecting all operating costs. These costs were computed from the following general expression.

Sum of all expenses = Sum of all revenues

which is developed further into the following algorithm.

$$SUM(1 + INT)^{Nn} = ODt/ha \times \left[REV/ODt * (1 + INT)^{N1} + REV/ODt \times (1 + INT)^{N2} + \ldots + REV/ODt \times (1 + INT)^{Nn}\right]$$

The above expression is rearranged to compute an average cost, or revenue, per oven dry tonne, by using the known inputs.

$$TFC = \left[(1 + INT)^{N1} + (1 + INT)^{N2} + (1 + INT)^{N3} + \ldots (1 + INT)\right]^{Nn}$$

$$REV/ODt = \frac{SUM \times (1 + INT)^{Nn}}{ODt/ha \times TFC}$$

where

SUM = the sum of all operational costs
ODt/ha = harvest yield in oven dry tonnes per hectare
REV/ODt = revenue in dollars per oven dry tonne
INT = real interest rate
N1, N2, N3, etc. = number of years to 1st, 2nd, 3rd, etc. harvest
Nn = the number of years to the last harvest
TFC = time related power factor

Cost of Land Operations per Oven Dry Tonne

The value of plantation land or that of the abandoned agricultural land has been assumed to be $750.00/ha for all computations; however, the value of the nursery land used for the plantation of whips is $2000.00/ha, an estimated average value of prime agricultural land. The number of rotations and the number of years to the first and to the last harvest are also introduced in the final computations of the cost per oven dry tonne of biomass.

The equipment used for land preparation operations must be transported to and from plantations; the cost of operations per hour is corrected by adding the cost of equipment transport to the cost of a productive operation hour. The cost of equipment transport is computed on the basis of a distance to the plantation site, as well as on the average speed of road travel, and also on the loading and unloading delays. The total distance travelled is then divided by the average road speed to obtain hours of transport operation. The cost of equipment transportation is then adjusted by the estimated time in hours needed for a return trip. This cost per round trip is then divided by the number of hours the equipment is used at that particular location to obtain the adjustment cost per hour of the equipment operation.

On an average plantation site of 20 ha, the land preparation operation will take 50 h to complete at an average productivity of 0.40 ha/PMh. The expected cost of the equipment transportation for three trips is $388.91,

which when divided by 50 operating hours gives the rate of adjustment of $7.78 per operating hour, making the low cost per productive machine hour of the land preparation operation $406.92. The equivalent value for the high cost of transportation is $595.37 for three transportation trips, or $11.91 per hour of land preparation operation, making the corrected high cost of land preparation operation $471.89 per operating hour.

The following expressions were used to arrive to the cost of land preparation per oven dry tonne of biomass which will be produced on that plantation.

$$LDR = LDV * INT$$

where

LDR = yearly return on land
LDV = estimated value of land per hectare
INT = real rate of interest

$$CLH = \frac{CSL}{LDP} + LDR$$

where

CLH = cost of land preparation per hectare
CSL = adjusted cost of land preparation per productive machine hour
LDR = yearly return on land per hectare
LDP = productivity of land preparation in hectares per productive machine hour

To arrive to the value of investment in terms of today's dollars, the cost per hectare is compounded by using a real rate of either 7% or 10%, depending on whether the input costs are low or high.

The cost is compounded to the last harvesting; in the case of a 5-year rotation plantation, with the expected four rotation periods, the cost is compounded by a power of 20.5, which accounts for four 5-year rotation periods, plus the initial period of approximately one half of a year between the land preparation operation and the planting operation. This approach assumes compounding of the initial cost of the operation through a period of 20.5 years, giving the total cost of investment at the last harvesting.

To arrive to a revenue per oven dry tonne of a harvest, the compounded sum of all costs is divided by the yield in oven dry tonnes per hectare at

the time of the harvest, multiplied by the time related factor, computed for the number of harvests, from the initial land preparation operation to the last harvest.

The cost of land preparation operations per oven dry tonne was computed by using the following expression.

$$REV/ODt = \frac{SUM \times (1. + INT)^{Nn}}{ODt/ha \times TFC}$$

where

SUM = the sum of all operational costs
ODt/ha = harvest yield in oven dry tonnes per hectare
REV/ODt = revenue in dollars per oven dry tonne
INT = real interest rate
Nn = the number of years to the last harvest
TFC = time related power factor

The cost of land preparation operations per oven dry tonne for a 5-year rotation plantation yielding 50 ODt is $8.28, or 26.1% of the total cost per oven dry tonne. The high cost for the same plantation is $11.17, also 26.1% of the total cost per oven dry tonne. The low cost for a 5-year plantation, yielding 60 ODt/ha, is $6.90/ODt, or 22% of the total cost per oven dry tonne; the equivalent high cost is $9.31/ODt, or 22.6% of the total cost per oven dry tonne.

The cost of land preparation for a 10-year rotation plantation, yielding 62 ODt/ha, is $9.77/ODt, or 31.7% of the total cost; the equivalent high cost is $11.25/ODt, or 29.4% of the total cost per oven dry tonne.

The cost of land preparation for the 2-year rotation plantation yielding 20 ODt/ha, is $13.77/ODt, or 24.4% of the total cost per oven dry tonne. The equivalent high cost is $17.72/ODt, or 22.5% of the total cost per oven dry tonne. The costs for the 2-year rotation plantation reflect the considerably smaller yield per hectare per harvest, as compared to 5- and 10-year rotation plantations.

Cost of Nursery Operations per Oven Dry Tonne

Nursery operations include all operations involved in production of hybrid poplar cuttings, from the establishment of whip plantations to whip harvesting and processing into cuttings. Costs of all these operations must be converted to the cost per oven dry tonne of the resulting plantation. This is done by computing the cost per 1000 cuttings for all nursery operations, which is then converted to the cost of cuttings per hectare for

a desired rotation. The cost per hectare is then converted to the cost per oven dry tonne per harvest of that hectare of hybrid poplar trees. The cost per hectare of whip plantation is computed by using the following algorithms,

$$LDR = LDV \times INT$$

where

LDR = yearly return on land
LDV = estimated value of land per hectare
INT = real rate of interest

$$CWH = \frac{CSW + LDR}{WHP}$$

where

CWH = cost of whip harvesting per 1000 whips
CSW = adjusted cost of whip harvest per hectare
LDR = yearly return on land per hectare
WHP = productivity per hectare in 1000's of whips

This cost per 1000 whips is then converted to a cost per 1000 cuttings by dividing it by the number of cuttings per whip.

The cost of whip plantation is calculated by computing all costs retaining to the whip plantation establishment, land preparation, nursery production, and planting of whip plantation. The following expressions are used to arrive at the cost of whip plantations. The total cost per hectare of the whip plantation is computed by adding all the costs of all whip plantation components.

$$CWC = \frac{NRC + RTP}{PWC} \times WPC$$

where

CWC = cost of cuttings per hectare of whips
NRC = cost of nursery per hour
RTP = cost of plant rental per productive hour
PWC = production of cuttings per hour in 1000's
WPC = 1000's of cuttings per hectare of whips

$$TWP = CLD + CPL + CTN + CWC$$

where

TWP = total cost per hectare of whip plantation
CLD = cost per hectare of whip land preparation
CPL = cost per hectare of whip planting operation
CTN = cost per hectare of whip tending operation
CWC = cost of cuttings per hectare of whip plantation

Whip plantations are usually harvested every year and are assumed to remain viable for several harvests. The average cost per harvest is obtained by using the following expression.

$$CST/HRV = \frac{SUM \times (1. + INT)^{Nn}}{NHR \times TFC}$$

where

SUM = sum of all operational costs per hectare
NHR = total number of whip harvests
CST/HRV = total cost per hectare per harvest of whips
INT = real interest rate
Nn = the number of years to the last harvest
TFC = time related power factor

The TFC, time related power factor, has been discussed in the previous section.

The cost of all whip production operations per hectare is then converted in the cost per 1000 cuttings, so that it can be later applied to the cost of the establishment of any plantation.

$$CSW = \frac{CST/HRV}{Wha/1000} \times NMW$$

$$CTS = \frac{CSW}{NMC}$$

where

CTS = cost of whip production per 1000 cuttings
Wha = number of viable whip stool per hectare
NMW = number of whips per stool
NMC = number of cuttings per whip
CSW = cost of whip production per 1000 whips

The total cost of all nursery operations per 1000 cuttings is computed by adding up all nursery operation costs, converted to costs per 1000 cuttings. This cost of nursery operations per 1000 cuttings is then

multiplied by the number of cuttings required for the establishment of the plantation, also expressed in 1000's of cuttings per hectare.

$$EST = (HRV + NRS + RNT + CTS) \times CTH$$

where

EST = all nursery costs per plantation per hectare
HRV = cost of whip harvesting per 1000 cuttings
NRS = cost of production of cuttings per 1000 cuttings
RNT = cost of plant rental per 1000 cuttings
CTH = 1000's of cuttings required for plantation

The above cost is converted to the cost per oven dry tonne by using the following expression.

$$REV/ODt = \frac{EST \times (1. + INT)^{Nn}}{ODt/ha \times TFC}$$

where

EST = all nursery costs per plantation per hectare
ODt/ha = harvest yield in oven dry tonnes per hectare
REV/ODt = revenue in dollars per oven dry tonne
INT = real interest rate
Nn = the number of years to the last harvest
TFC = time related power factor

The cost of nursery operations for a 5-year rotation plantation with a yield of 50 ODt/ha is $0.82/ODt, or 2.6% of the total cost per oven dry tonne. The equivalent high cost is $1.41/ODt, or 3.3% of the total cost per oven dry tonne.

The cost of nursery operations for the 10-year rotation plantation having a yield of 62 ODt/ha is $0.24/ODt, or 0.8% of the total cost per oven dry tonne; the high cost is $0.42/ODt, or 1.1% of the total cost.

In contrast to the above low costs per oven dry tonne for 5- and 10-year rotation, the cost of nursery operations for the 2-year rotation is considerably higher. The cost for 2-year rotation with a yield of 20 ODt/ha is $10.19/ODt, or 18% of the total cost per oven dry tonne; the equivalent high cost is $16.79/ODt, or 21.4% of the total cost per oven dry tonne.

The cost for the 2-year rotation plantation is greater than those of the other rotations because of the high number of cuttings required to

establish the plantation and because of a relatively low biological productivity per hectare per harvest, compared to the biological productivity of 5- and 10-year rotation plantations.

Cost of Planting Operation per Oven Dry Tonne

As in the case of the land and nursery operations, the planting operation is the basic operation in the establishment of short rotation forests. The cost of planting, as well as the benefits of planting, are spread throughout the life of the plantation. To arrive at the cost per oven dry tonne, the cost per hectare is applied to the following expression, developed in previous subsections.

$$REV/ODt = \frac{PLT \times (1. + INT)^{Nn}}{ODt/ha \times TFC}$$

Where

PLT = all planting costs per hectare
ODt/ha = harvest yield in oven dry tonnes per hectare
REV/ODt = revenue in dollars per oven dry tonne
INT = real interest rate
Nn = the number of years to the last harvest
TFC = time related power factor

The planting cost for the 5-year rotation plantation yielding 50 ODt/ha, is $1.17/ODt, or 3.7% of the total cost per oven dry tonne; equivalent high cost is $2.12/ODt, or %5 of the total cost.

The cost for the 10-year rotation, with a yield of 62 ODt/ha, is $0.87/ODt, or 2.8% of the total cost; the high cost is $1.35/ODt, or 3.5% of the total cost per oven dry tonne.

The cost for the 2-year rotation is $2.87/ODt, or 5.1% of the total cost; the high cost is $4.95/ODt, or 6.3% of the total cost per oven dry tonne.

The main factor that influences the cost per oven dry tonne seems to be the yield per hectare, which makes the cost for the 2-year rotation plantation higher then the costs for the 5- and 10-year rotation.

Cost of Tending Operation per Oven Dry Tonne

Tending operation is assumed to affect only one harvest, its cost is applied to one harvest yield per hectare, and it is compounded for the period from time of tending to the next harvest. The following expression

is used to compute the recovered cost of tending per oven dry tonne of the harvest yield.

$$REV/ODt = \frac{TND \times (1. + INT)^{n}}{ODt/ha}$$

where

TND = all tending costs per hectare
ODt/ha = harvest yield in oven dry tonnes per hectare
REV/ODt = revenue in dollars per oven dry tonne
INT = real interest rate
n = the number of years to the next harvest

Cost for mechanical tending only for the 5-year rotation plantation yielding 50 ODt/ha is $2.22/ODt, or 7% of the total cost per oven dry tonne; the equivalent high cost is $3.21/ODt, or 7.5% of the total cost. The operation was assumed to take place in the third year for n = 2.5 years.

The cost of a single application of weed control chemicals in the 10-year rotation plantation, with a yield of 62 ODt, is $2.77/ODt, or 9% of the total cost; the high cost is $3.27/ODt, or 8.5% of the total cost per oven dry tonne. Tending is assumed in the eighth year, for n = 2.5 years.

The cost of a single mechanical tending operation for a 2-year rotation plantation, yielding 20 ODt/ha, is $1.79/ODt, or 3.2% of the total cost; the high cost is $2.58/ODt, or 3.3% of the total cost. A multi-row tending operation in the 2-year rotation plantation is assumed done in the first year of the growth for n = 1.5 years.

Costs of tending operations per oven dry tonne vary with the type of the tending. The application of chemical weed control is somewhat costlier then mechanical tending only; it is also more expensive then the combined mechanical tending with the application of the fertilizer.

Cost of Harvesting Operation per Oven Dry Tonne

Harvesting operations apply to one yield per hectare, and, since the costs in this study are given in constant 1985 dollars, the cost per oven dry tonne is computed simply by dividing the adjusted cost of the operation per hectare by the yield in oven dry tonnes per hectare. All costs per productive machine hour are adjusted for the cost of equipment transportation.

The cost of harvesting for a 5-year rotation plantation yielding 50 ODt/ha is $6.23/ODt, or 19.6% of the total cost per oven dry tonne; the high cost is $8.09/ODt, or 18.9% of the total cost/ODt.

The cost of harvesting for a 10-year rotation plantation with a yield of 62 ODt/ha is $4.11/ODt, or 13.4% of the total cost per oven dry tonne. The equivalent high cost is $5.24/ODt, or 13.4% of the total cost/ODt.

The cost of harvesting in a 2-year rotation plantation yielding 20 ODt/ha is $14.60/ODt, or 25.9% of the total cost per oven dry tonne; the equivalent high cost is $19.50/ODt, or 24.8% of the total cost.

As in the case of other costs, the cost of harvesting operations per oven dry tonne reflects directly the yield in oven dry tonnes per hectare of a given rotation.

Cost of Chipping Operation per Oven Dry Tonne

As in the case of harvesting, the cost of the chipping operation stands on its own; it is presented in constant dollars. The total cost of the operation is divided by the output of the operation in oven dry tonnes.

The cost of the chipping operation is almost identical for all rotations; the variation is due to a small variation in the cost correction for the transportation of the equipment to and from the plantation site, which is affected by the yield per hectare that varies for different rotations.

The cost of chipping per oven dry tonne varies between $7.28 and $7.50 for different rotations; the high cost is between $9.53/ODt and $9.87/ODt. The percentage of the total cost per oven dry tonne is 13.3% for the 2-year rotation, 23% for the 5-year rotation, and 23.7% for the 10-year rotation plantation.

Cost of Chip Transportation per Oven Dry Tonne

The total cost of transportation is divided by the productivity of the system in oven dry tonnes, giving the cost per oven dry tonne.

The cost per oven dry tonne is identical for all rotations, depending only on the original estimates of cost inputs and on the computed productivity of the transportation system.

In this analysis the cost is $5.74/ODt; the high cost is computed as $7.25/ODt. The percentage of the total is 18.7% for the 10-year rotation, 18.1% for the 5-year rotation, and 10.2% for the 2-year rotation. The

variation in percentages is due to the variation in the total costs per oven dry tonne for different rotations.

TOTAL COST PER OVEN DRY TONNE FOR ALL OPERATIONS

The total operational cost per oven dry tonne is a function of: rotation periods, operational costs per hectare, with perhaps the most important factors being biological and mechanical productivity per hectare. This study analysed several variations of rotations and their inputs; however, only the most pertinent costs per oven dry tonne are illustrated and discussed.

Cost per Oven Dry Tonne for 5-Year Rotation Plantations

The total cost per oven dry tonne of all operations for a 5-year rotation plantation with a yield of 50 ODt/ha is illustrated in Fig. 30. The cost is based on a 6-row planting operation, 4-row harvester, and a single mechanical tending in the third year. The total cost is $31.76/ODt, with the highest cost components being land preparation, chipping, harvesting, and transportation of chips. The other three operations, tending, planting, and nursery, are relatively inexpensive and do not effect the overall cost greatly; however, the cost of tending varies with the type of tending application and may become fairly significant as a percentage of the overall cost.

The high cost for the same plantation, but with higher equipment costs and a 10% real interest rate, is $42.80/ODt. The order of the magnitude of seven components is similar to that illustrated in Fig. 30.

The cost of operations per oven dry tonne for a 5-year rotation plantation yielding 60 ODt/ha is illustrated in Fig. 31; all operations are the same as those discussed for the 50 ODt/ha plantation, except for the single tending operation, which is a combined mechanical tending together with the application of the fertilizer; this is assumed to potentially increase the yield by 20%, from 50 to 60 ODt/ha (Strauss et al., 1984). This increase is speculative, based on the interpolation of a 4-year experiment brought down to a single application. The total cost of $31.42/ODt is not much lower than the cost for the 50 ODt/ha plantation, because of the increased cost of the tending operation. The equivalent high cost/ODt for the 60 ODt/ha plantation is $41.19/ODt. The difference of $0.32 is not a sufficient incentive for the additional cost of the application of the fertilizer; however, the cost is based on the extrapolation of experimental results which would change in the light of operational experience.

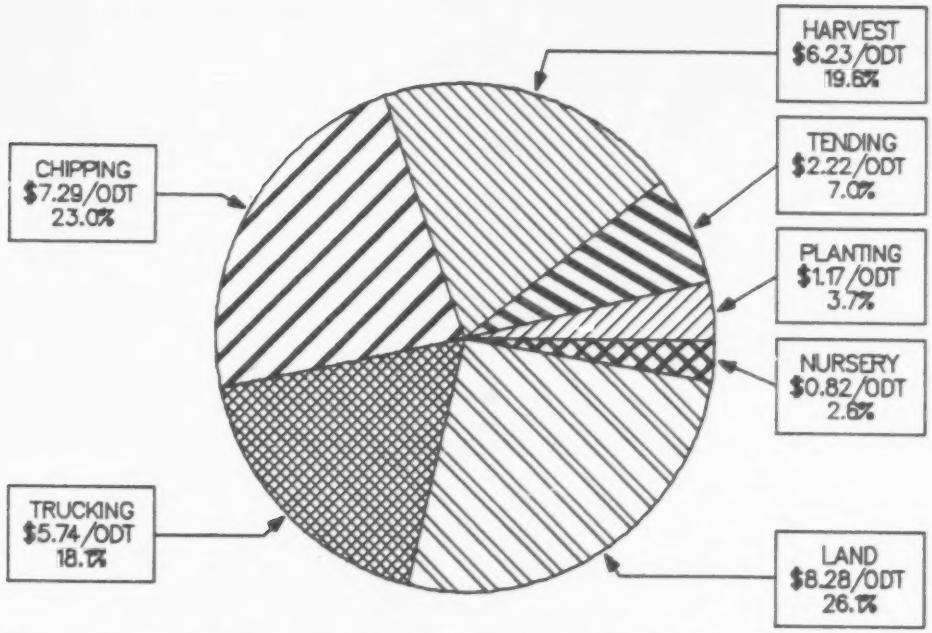

Figure 30. Cost/ODt for 5-year rotation plantation with a yield of 50 ODt/ha. Total operational cost is $31.76/ODt

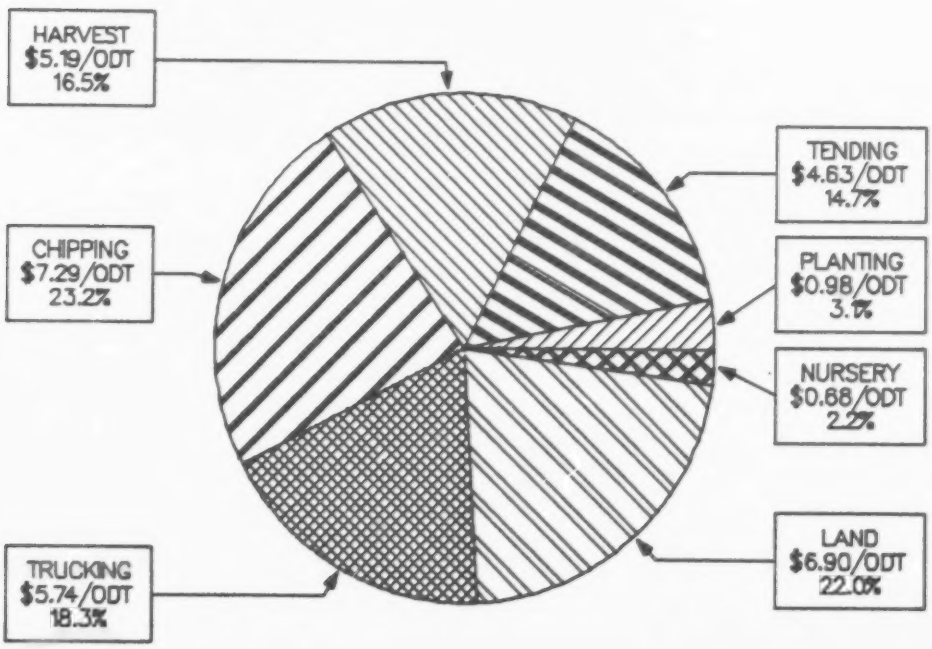

Figure 31. Cost/ODt for 5-year rotation plantation with a yield of 60 ODt/ha. Total operational cost is $31.42/ODt

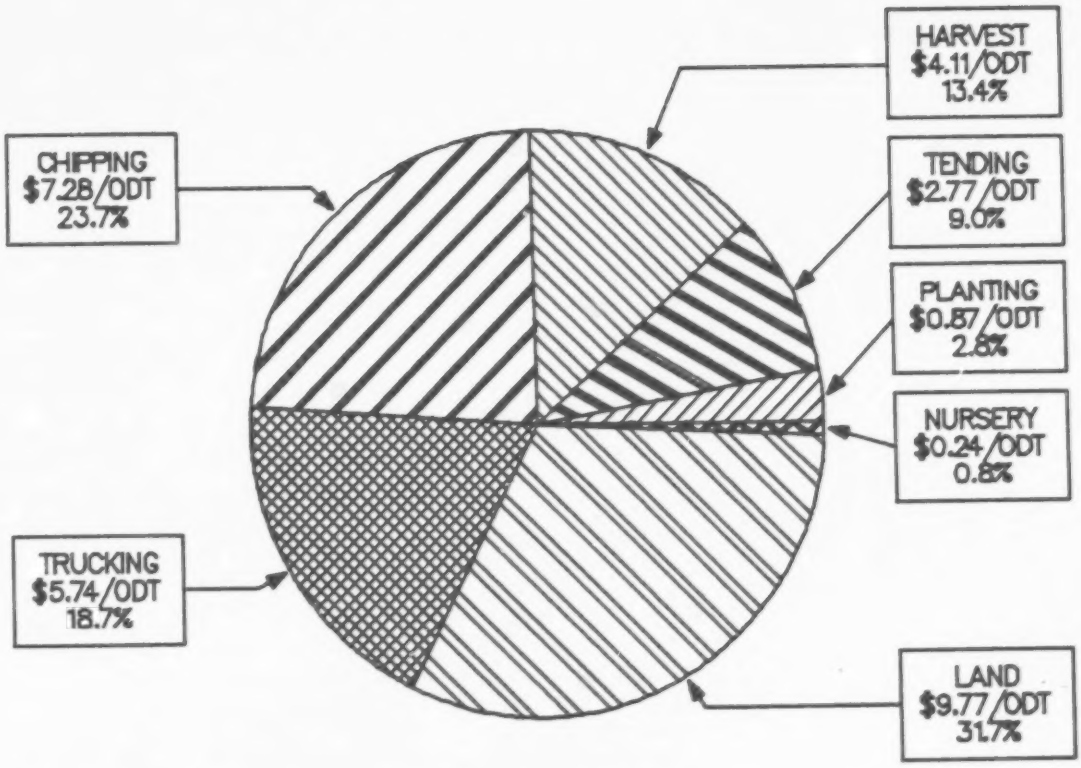

Figure 32. Cost/ODt for 10-year rotation plantation with a yield of 62 ODt/ha. Total operational cost is $30.78/ODt

The above costs are based on potentially realistic yields per hectare; however, the 6-row automatic planter and the 4-row harvester are still technically conceptual machines based on the development work done by the Bioenergy Program of the National Reaserch Council of Canada. Some of the concepts have been tested, and the machines are considered technically feasible. The cost of harvesting and the total cost per oven dry tonne would increase by $2.01/ODt if a 2-row harvester is used, and it would increase by $4.65/ODt when a single-row harvester is used. A single-row harvester has been tested and is considered a commercially acceptable machine.

Cost per Oven Dry Tonne for 10-Year Rotation Plantations

The total cost per oven dry tonne for 10-year rotation plantation, with a yield of 62 ODt/ha is illustrated in Fig. 32. The cost of $30.78/ODt is based on a 4-row planting operation, 2-row harvester, and a single application of weed control chemicals in the eighth year. The highest component cost is the cost of the land preparation operations of $9.77; this comparatively large cost, accounting for 31.7% of the total, is due to

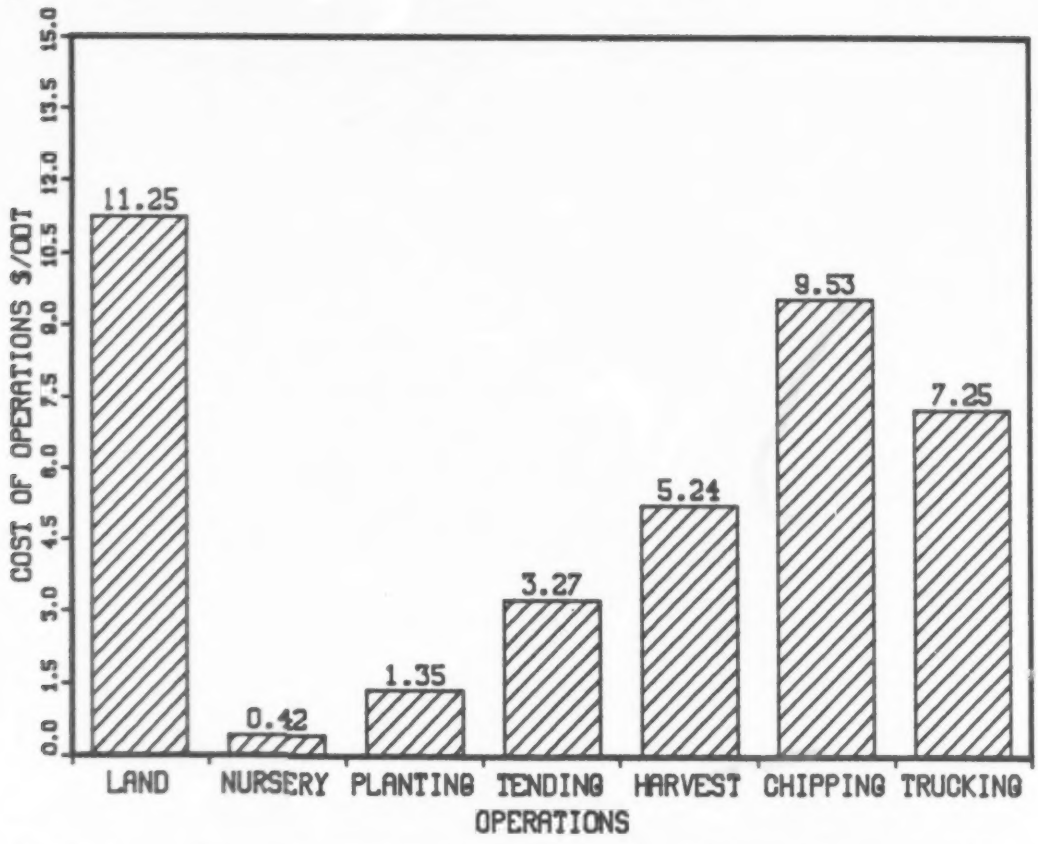

Figure 33. High cost/ODt for 10-year rotation plantation with a yield of 62 ODt/ha. Total operational cost is $38.32/ODt

the long period of time required for the amortization of the initial operational costs. The equivalent total high cost of $38.32/ODt is illustrated in Fig. 33, with the main increase in those operations having the largest mechanization capital inputs.

The above costs are based on the use of a 2-row harvester; if a single row harvester was used, the overall cost and the cost for the harvesting operation would be decreased by $1.81/ODt.

Cost per Oven Dry Tonne for 2-Year Rotation Plantations

The total cost per oven dry tonne for the 2-year rotation plantations, with a yield of 20 ODt/ha is illustrated in Fig. 34. The cost of $56.47/ODt is based on a 6-row planting operation, a 4-row harvester, and a mechanical tending during the first year of growth; no fertilizer application is assumed. The equivalent high cost is $78.66/ODt. The cost of nursery operations is relatively high because of the high number of cuttings used to establish the plantation.

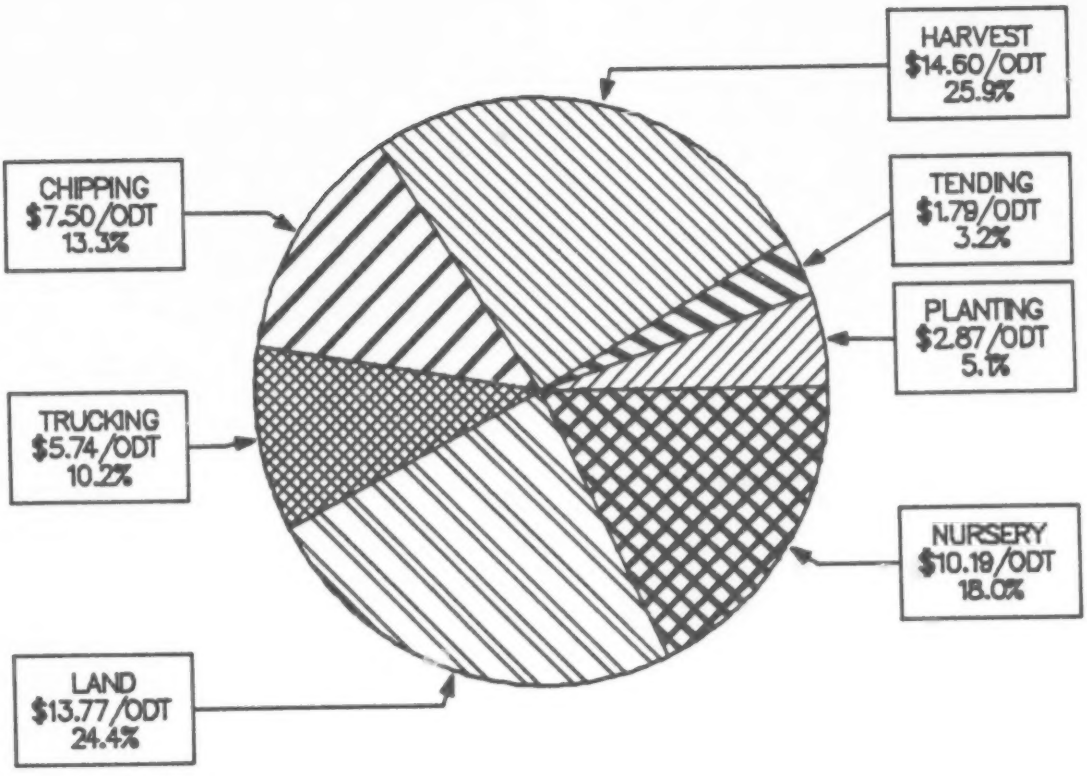

Figure 34. Cost/ODt for 2 year rotation plantations with a yield of 20 ODt/ha. The total operational cost is $56.47/ODt

The very high total cost, compared to the 5- and 10-year rotation plantations, is due to the low yield of a 2-year rotation plantation. The economic advantages of the high mechanization do not improve the productivity of operations sufficiently to considerably improve the total cost per oven dry tonne.

The cost is based on the use of a 4-row harvester, if a 2-row harvester were used the cost of harvesting and the total cost would increase by $3.34/ODt.

A possible higher yield can be achieved by applying fertilizer during the first year of growth. An assumed 20% increase in the yield due to the application of fertilizer would bring the yield to 24 ODt/ha. The total cost per oven dry tonne of a plantation yielding 24 ODt/ha per hectare is illustrated in Fig. 35. The total cost of $49.05/ODt reflects the improved yield of the plantation. The equivalent high cost is $70.24/ODt.

Some reports expect the total yield of 18 ODt/ha per harvest for a typical 2-year rotation plantation; the total cost for this plantation per

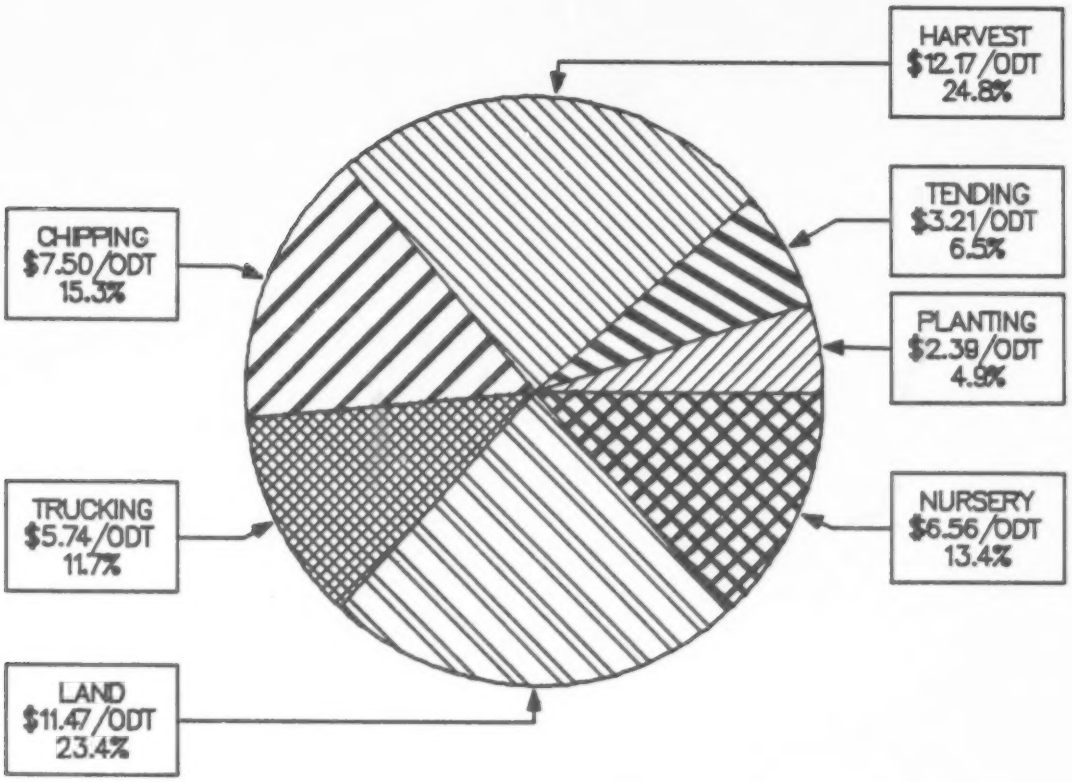

Figure 35. Cost/ODt for 2-year rotation plantations with a yield of 24 ODt/ha. Total operational cost is $49.05/ODt

oven dry tonne was computed at $63.56/ODt, and the equivalent high cost is $87.94/ODt.

Some reports expect the total yield of 18 ODt/ha per harvest for a typical 2-year rotation plantation; the total cost for this plantation per oven dry tonne was computed at $63.56/ODt, and the equivalent high cost is $87.94/ODt.

The low biological productivity per harvest of 2-year rotation plantations account for high costs per oven dry tonne, compared to the costs per oven dry tonne of 5- and 10-year rotation plantations.

MACHINE DEVELOPMENT

The cost of short rotation forest wood must compete with the cost of wood waste, or at the best, with the current price of wood from woodlots and from forests. The price of $49.00/ODt for wood chips delivered to the pulp mill is what the users are prepared to pay on the open market. At the cost of approximately $31.50/ODt, established in the previous chapter, there is a difference of $17.50/ODt, between the market price and the projected cost of wood chips produced by a SRF system. To obtain that price range, the cost of SRF operations must be controlled and brought down to become competitive with the existing wood prices.

If we assume that we cannot increase the biological productivity in a relatively short time period, the only solution left is to organize and mechanize SRF operations to obtain the desired range of productivity and reduce the cost of producing wood chips.

Operations involved in the process of developing SRF plantation and producing wood are a mixture of intensive agricultural operations with some new, typically agro-forest based operations, such as specialized planting, harvesting of trees in a massive, agricultural manner, and the usual forest operations requiring chipping and transportation of wood chips.

Since the mechanization of SRF is a relatively new development area, not much has been published concerning past work (Crafoord et al., 1980; Jones, 1983; Golob, 1982; Mattson, 1983; Curtin and Barnett, 1985). Most published reports discuss the mechanization of SRF harvesting operations, with some mention of difficulties associated with the development of automatic planting machines.

During the early spring and fall plantation terrain is often quite soft, making planting operations and early harvesting difficult.

TERRAIN-VEHICLE-SYSTEMS DEVELOPMENT

In this program, the analysis of terrain properties and of potential problems associated with vehicle performance in soft terrain was done concurrently with the development of machines. Some relatively recent reports discuss the subject of terrain-machine interaction, applied to forestry and agro-forestry (Bekker, 1980; Golob, 1978), reflecting on the importance of the terrain-vehicle analysis for a successful development of agro-forestry machines.

The Bioenergy Program of the NRCC completed several studies in the area of terrain-machine interaction, including discussions on the basic

theory and analysis (Bekker, 1983, 1985), measurement and recording of soil strength data (Wong, 1983)[1] and on soil-tool interaction.[2]

Also, the Bioenery Program developed computer software for the analysis and evaluation of soil strength measurements,[3] and on prediction of wheeled vehicle performance in soft soils.[4]

All studies were of a relatively general nature, with the exception of the work done in the accumulation of soil strength data, which were intended to be used for a correlation analysis of soil strength parameters and soil types. This correlation could be applied to predict performance of vehicles, based on soil types and their moisture content.

MACHINES FOR LAND PREPARATION

Of the three main land preparation operations, the established agricultural operations, such as plowing, harrowing, and disking, are available and can be controlled to obtain the optimum operational cost for a given productivity; however, the brush removal operation and the removal of roots and stones may be improved to reduce the overall cost of the land preparation operations.

Brush Harvester

The Bioenergy Program of the NRCC has been involved in contract development of an attachment for a small agricultural tractor that would cut and

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[1]Sloot, E.A. 1984. Soil testing program. National Research Council of Canada, Ottawa, Canada. NRCC Int. Contr. No. 05SR.31926-4-5005.

[2]Bilanski, W.K., and L'Esperance, A.L. 1986. Soil-tool mechanics study. National Research Council of Canada, Ottawa, Ontario. NRCC Contr. No. 22st.31025-4-5064.

[3]Wong, J.Y., and Prestonne-Thomas, J. 1984. Implementation of a computer program for processing terrain data. National Research Council of Canada, Ottawa, Ontario. NRCC Int. Contr. No. 03-1984/6169.

[4]Wong J.Y., and Prestonne-Thomas, J. 1986. Implementation of a computer program for wheeled vehicle performance prediction. National Research Council of Canada, Ottawa, Canada. NRCC Int. Contr. No. 0SZ85-00054.

collect brush from abandoned agricultural land (Anon, 1983c).[1],[2] The operation was designed as a continuous harvesting of the brush wood in a 2-m wide swath, at an average ground speed of 2.5 km/h. This machine is shown in Fig. 36.

The most difficult development area is the cutting system, that will continuously cut a 2-m swath of brush. The cutting device consists of two parallel reciprocating saw-like knives, driven by a hydraulic motor; the knives work against each other, thus preventing brush from sliding sideways with the motion, as it would be in the case of a single knife. A study of dynamic and kinematic stability of the reciprocating device, conducted by the Centre de Recherche Industrielle du Québec, indicates that the principle of the operation is technically sound.[2] The two cutting bars have a stroke of 14 cm and are driven by a 37 kW hydraulic motor at a speed of 500 rpm; a desired linear speed of cutting knives is estimated to be between 7 and 10 m/s. The energy storage is achieved by means of compression springs, which are active in the return strokes of the cutting bars; the maximum size of the brush stem is estimated to be 13 cm; however, the maximum cumulative length of the cross-section cut is also estimated to be 13 cm, at any given time.

The gathering and accumulating mechanism extends through the width of the cutting bar, and it will have three sets of collecting arms on each side of the accumulator. The arms will act automatically in sets, one set collecting, one compacting, and one pulling from under the collected brush in a sideways motion, ready for the next collecting stroke.

An added design feature calls for a swing pivot arrangement, whereby the cutting and accumulating device will be capable of swinging about a pivot at one side of the machine, converting the harvester from cutting in front of the tractor to the side cutting attachment, equipped with a direct back unloading mechanism. This prototype has not been built as yet; the components are in various stages of design and manufacturing and may not be built and tested. Due to lack of funds this project was terminated.

Root Cutter-Collector

Once the brush has been removed, the remaining stumps, roots, and stones need to be cut, dug out, loaded on a field vehicle of some kind,

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[1]Wozniak, B. 1984. Brainstorming Sessions. School of Industrial Design. Carleton University, Ottawa, Ontario. NRCC. Int. Rep. Contr. No. OST83-00231.

[2]Hamilton, D.D. 1985. Development of a brush harvester. Logging Development Corporation, Montreal, Quebec. NRCC Int. Rep Contr. No. OSR84-00129.

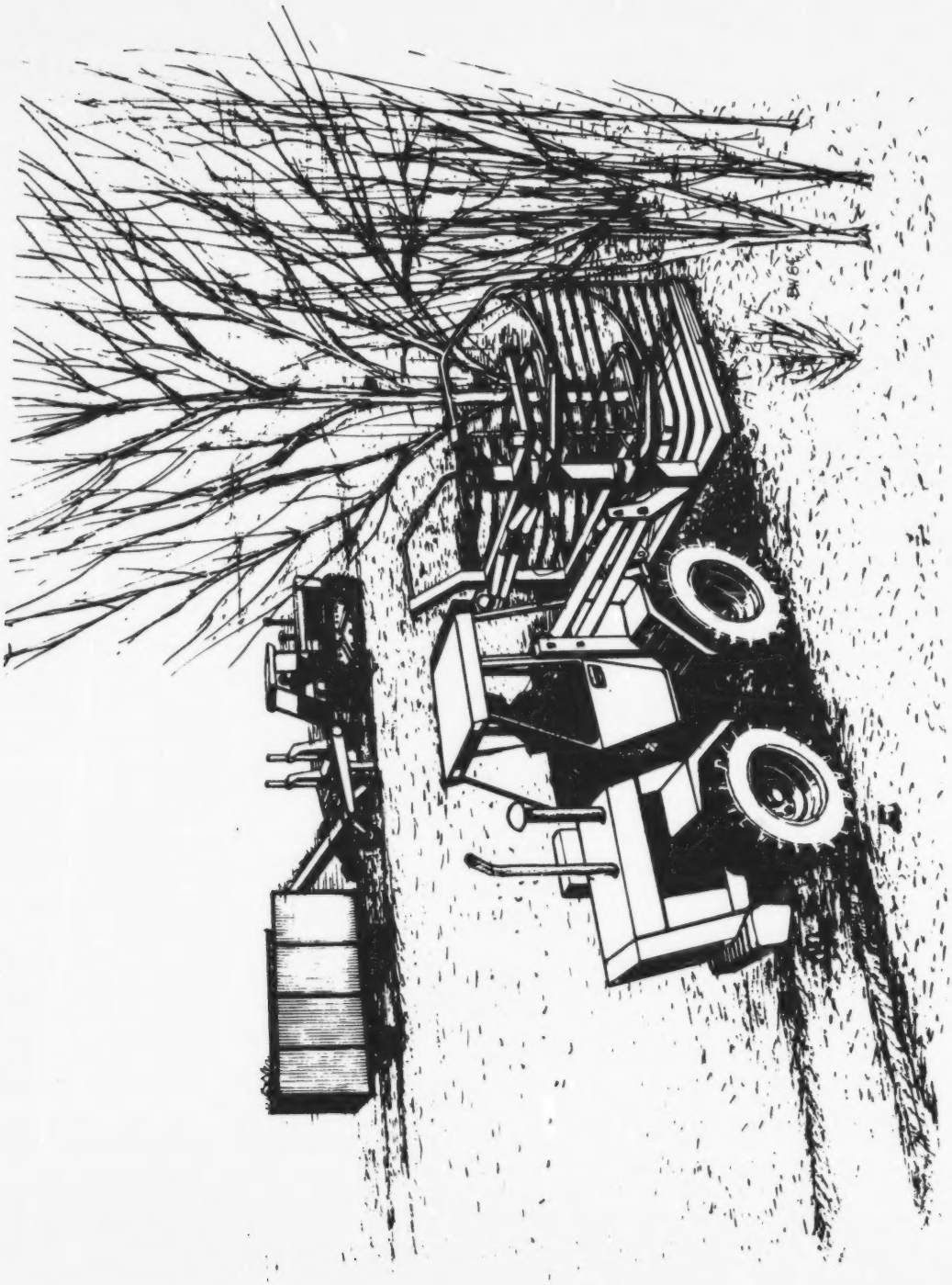

Figure 36. Brush harvester

and removed from the field. The equipment to do these operations on an individual basis is to a degree available; however, it requires several different machines, and it is time-consuming and costly. The NRCC conducted a contracted feasibility study to define design parameters of a machine that would cut, collect, and remove roots, as well as stones, in a one pass operation (Anon, 1983c; Elms, 1984).[1,2] The proposed concept is shown in Fig. 37.

The above proposed design concept represents a machine that is pulled by a heavy, 225 kW tracked tractor; the root cutter power requirement is estimated at 115 kW, and the extractor and conveyer-elevator system is estimated to require an additional 75 kW. The extractor, or separator wheel, and the elevator are driven hydraulically.

The operator would plan the runs so that the container can be emptied at the roadside, for an easy removal from the site.

The project was not carried on into design and manufacturing stage, because of other pressing development requirements.

MACHINES FOR NURSERY OPERATIONS

This analysis is concerned with the development of machines for use in the overall production of hybrid poplar cuttings; this includes the production of whips as well as the actual production of cuttings from whips. The two operations are treated separately because the machines involved in planting and harvesting of whips are of different nature from the machines that produce cuttings. The planting machine will be discussed separately, because the same automatic planter that will plant production plantations will also plant whips.

Whip Harvesting Machines

Harvesting of whips requires a machine similar to the machine for the 2-year rotation plantation. The spacing of whips is the same as the spacing of the 2-year rotation plantation. However, whips are harvested every year, they have smaller diameter stems and are considerably shorter then the 2-year growth.

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[1] Wozniak, B. 1984. Brainstorming Sessions. School of Industrial Design. Carleton University, Ottawa, Ontario. NRCC. Int. Rep. Contr. No. OST83-00231.

[2] Elms, R.G. 1984. Feasibility study and design concepts of a root cutter and collector. Elms Design Inc., Ancaster, Ontario. NRCC Int. Rep. Contr. No. OSX83-00126.

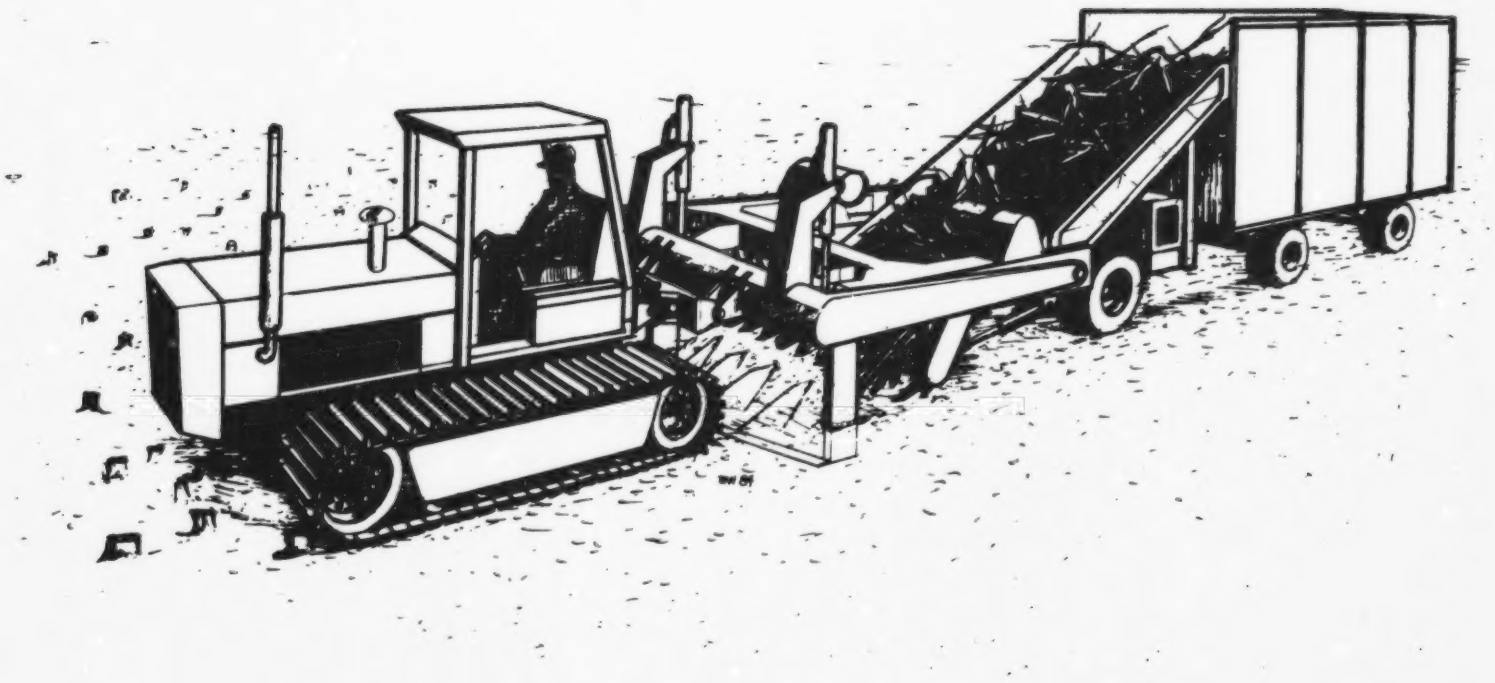

Figure 37. Root cutter-collector

The Bioenergy Program of the NRCC developed on contract (Anon, 1983c);[1],[2] an attachment for a small farm tractor, for the harvesting of nursery whips used to make poplar cuttings. The only other experimental whip harvester prototype is the attachment developed by the Ontario Ministry of Natural Resources (Jones, 1983). The machine developed by the NRCC is illustrated in Fig. 38. The front mounted attachment is designed with a continuous input chain type conveyer that pushes severed stems of whips into the gathering mechanism, which packs them into the whip accumulator. The machine was designed to operate on the same face of the plantation, back and forth; this is done with two accumulators, so that, when turning at the end of the row, the operation is switched to the accumulator on the clear side of the machine.

One of the design requirements was a clean cut of the very fragile stems to prevent microbial attack and spoilage of the stems; because of the very sensitive nature of whip stems, the band saw type severing device was incorporated in the NRCC prototype for field testing. The hydraulic oil flow to the saw motor is 1.77 dm^3/s or L/s, at a system pressure of 17.24 MPa the maximum power requirement is 30 kW. Since the project was terminated, it has not been established whether this power requirement is overestimated.

The linear speed of the band saw is 40 m/s, and the kerf is 3 mm thick. The initial tests indicated a smooth cut, with no damage to the stem. The band saw device is illustrated in Fig. 39.

The stems are accumulated and, when the bunch is of the right size, it is tied by an agricultural binder and ejected onto the ground.

All controls are automatic with a manual override. Automatic control hardware is composed of a microprocessor, equipped with a programmable controller, that can be programmed and modified as required. The advantages of the microprocessor controls are many: improved reliability, less space required, less expensive than the equivalent hard-wired system, programmable as requirements change, and generally more flexible than the hard-wired control system. The total hydraulic oil flow to the control system is 0.76 L/s. The total required power for the attachment is 43 kW.

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[1]Wozniak, B. 1984. Brainstorming Sessions. School of Industrial Design. Carleton University, Ottawa, Ontario. NRCC. Int. Rep. Contr. No. OST83-00231.

[2]Jasinski, S.K., and Sulima, S.C. 1985. Development of a whip harvester for hybrid poplar cuttings. HYD-MECH. Forestry Ltd., Woodstock, Ontario. NRCC Int. Rep. Contr. No. OSX83-00104.

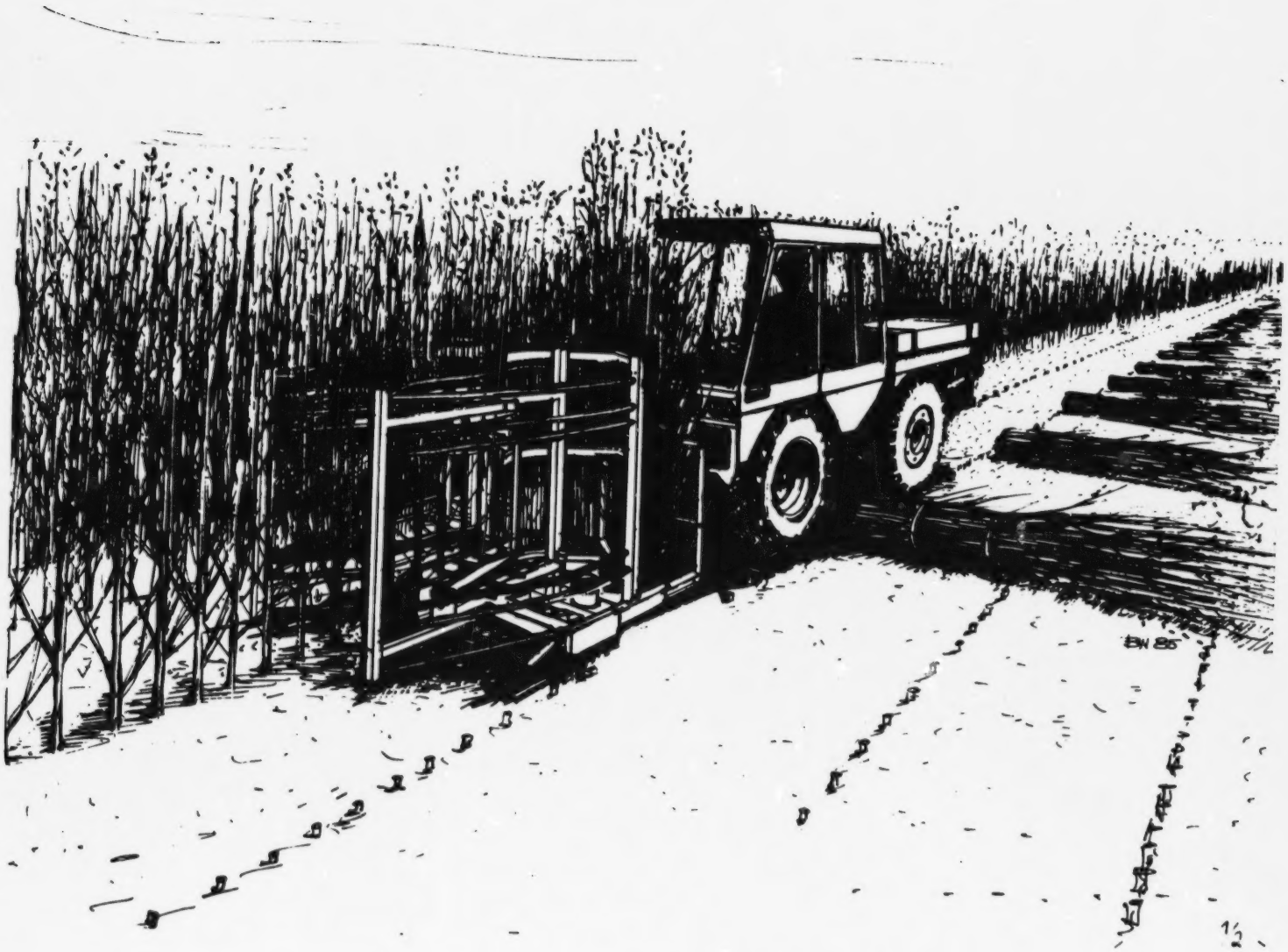

Figure 38. NRCC whip harvester

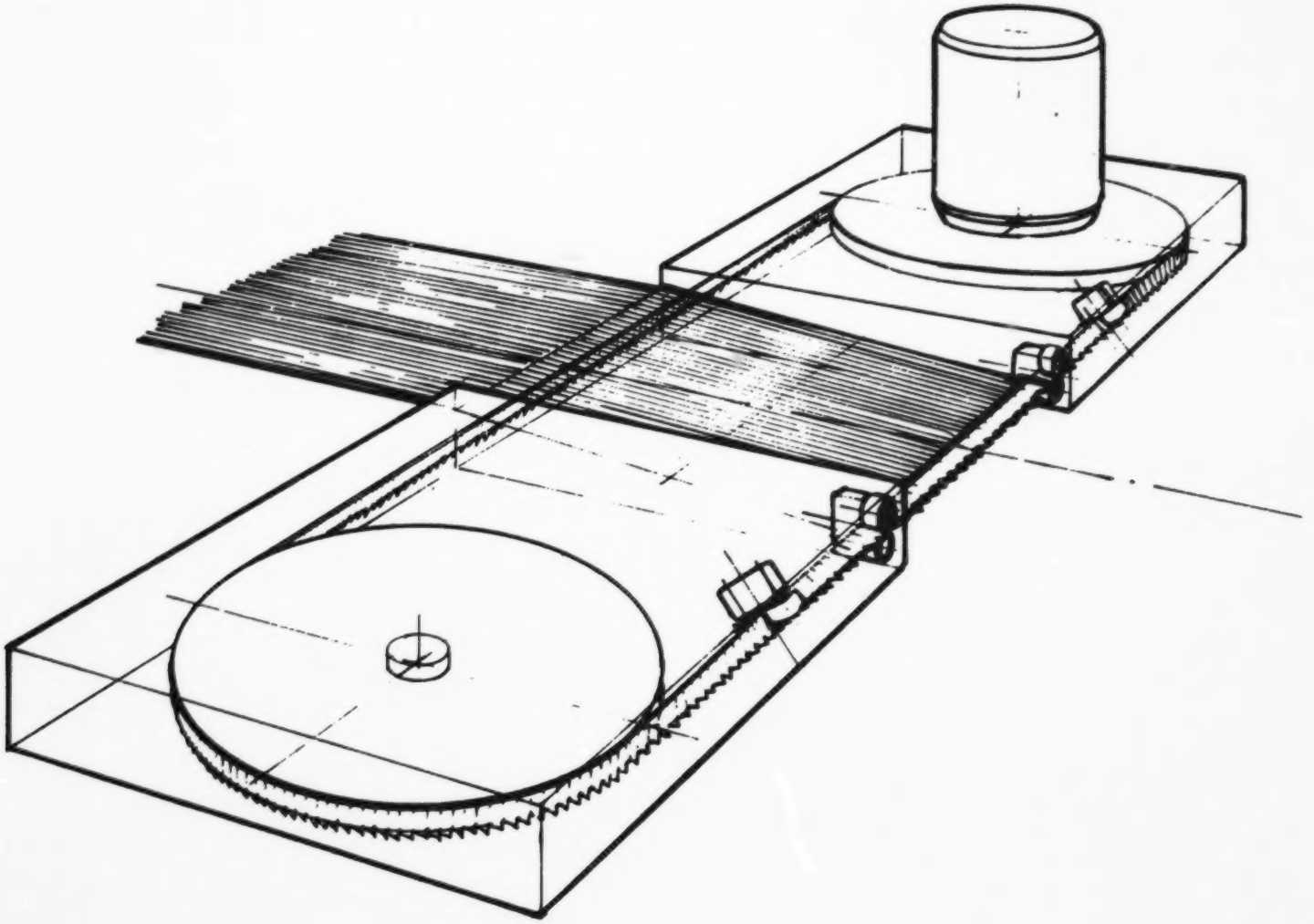

Figure 39. Band saw severing device for whips

Several potential problem areas have been observed during the initial testing; the infeed conveyer does not control the movement of the stems at the lower end, when in contact with the platform floor. A possible solution may be an additional lower drive for the stems, to prevent the butt ends of stems from lagging. The stem packing device may present a problem in the area between the conveyer and the packing chamber. The agricultural binder will need redesign, because it does not produce tight enough bundles. These difficulties should be resolved before the machine is accepted as a commercially viable product.

The support equipment required to collect and transport bundles of whips to the nursery production plant is illustrated in Fig. 3. The machines and equipment needed for the operation are standard, readily available; the only system component that may require some design work is the field wagon pulled by a tractor. These wagons should be designed to receive the optimum number of bundles of whips; most likely, these bundles will be placed across the platform, not lengthwise.

Machines for Production of Cuttings

Once cut and bundled the whips are taken to the production plant where they are sorted and cut to 25-cm long cuttings. The work in the plant can be divided into three separate areas. The first stage is the receiving and transit storing of bundles in the process of being delivered to the production line for processing into cuttings; in the second stage the whips are singularized, debranched, cut to length, sorted, and inspected; in the third stage of work the cuttings are placed in containers, sealed, and placed in the cold storage area. These operations are at present mostly done by hand and are very labour intensive. The handling of whips between the field wagon and the receiving bin is fairly simple and can be improved with the existing handling equipment.

The actual operation of producing cuttings is the most labour intensive, very costly and time consuming. The NRCC has done contract development work in the analysis, feasibility, and preliminary laboratory testing of various aproaches that would automate the production of cuttings (Anon, 1983c.[1] [2] The proposed automatic production line, based on conclusions of the feasibility study, is illustrated in Fig. 40.

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[1]Wozniak, B. 1984. Brainstorming Sessions. School of Industrial Design. Carleton University, Ottawa, Ontario. NRCC. Int. Rep. Contr. No. OST83-00231.

[2]Bedard, J.T. 1985. Production de boutures de peupliers. Centre de Recherche Industrielle du Québec, Québec. NRCC Int. Rep. Contr. No. OSX83-00150.

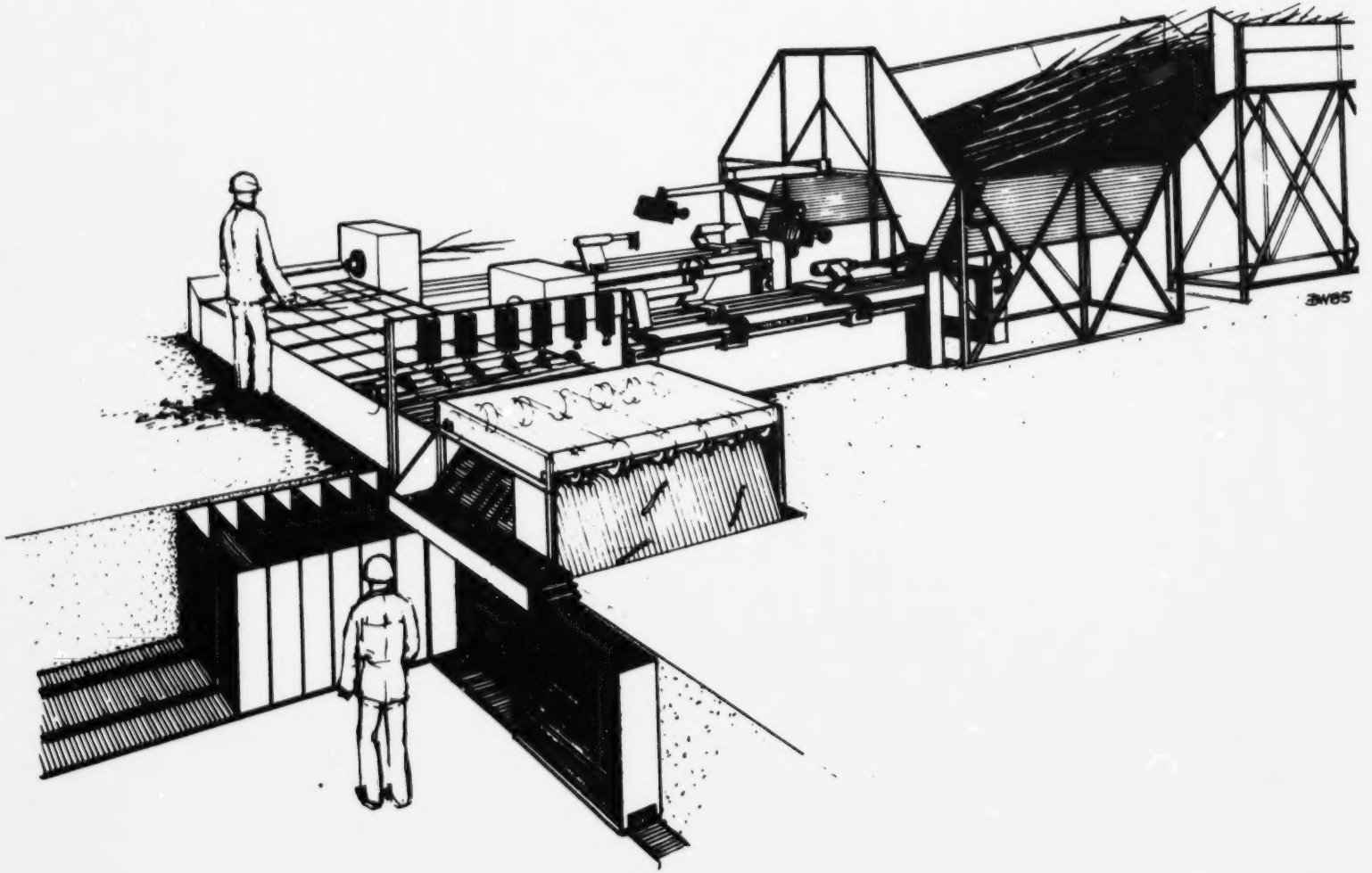

Figure 40. Automated production of cuttings

The main production area is located between the bin with whips and the machine in the foreground that packages and seals cuttings in containers.

In the illustration are shown two devices for recognition and singularization of whips and two delimbing heads. The bin with whips is V-shaped to allow for a gradual movement of whips towards the device that will identify and pull them out of the bin.

The initial trials with the singularization of whips included a grabbing device that picked one whip from the opening at the V-shaped bottom of the bin. That device was mechanical; it did not involve any visual recognition equipment. However, the device was considered unreliable.

The arrangement in the illustration is the final proposal, with a visual recognition system, that identifies, grabs, and pulls out the identified whip. The visual image analyser has been tested and it seems to be the best approach so far developed for the singularizing process. The pulling device depends on the mechanism that will grab the end of the whip and then pull it out of the bin. The initial approach was to develop grabbing fingers to pick out the whip; however, that presented difficulties in grabbing only the whip identified by the visual recognition camera. The last test included a head equipped with a drill that drilled into the end of the whip, and the secured whip was then pulled out and placed in the debranching head. The delay, or time required to select, grab, and pull out the whip, was estimated at 5 to 6 s. This time requirement is very important for the overall productivity of whips per delimbing head, if other time-related factors are kept constant, and if the average usable length of the whip remains the same. With the delay of 5 s and the delimbing speed of 1 m/s, the productivity is approximately 3000 cuttings per head per hour.

The speed of delimbing depends on the manner in which whips are delimbed; the initial tests were done with a device where whips are pulled through a set of delimbing knives at a relatively high speed. However, this approach proved unsuccessful, and various other designs were considered and tested. The best approach was narrowed down to a rotating delimbing head, equipped with three, high revolution cutting knives, spaced at 120° to each other, which rotate at 19 500 rpm, and at the same time, the whole delimbing head rotates around the whip at 500 rpm. The optimum radial distance between the delimbing head guide and the whip is estimated to be 2 mm; the axial distance between the guide and the rotating knives should be approximately 5 cm. It became clear that the speed of debranching depends on the desired remaining length of the branch stub. The stub 3 to 16 mm long requires a delimbing speed of no more then 1 m/s; the length of the stub and speed of delimbing depend on the type of the knife used in the delimbing head. The results are not conclusive, and it was decided

that an additional year of development is required, to establish the optimum cutting device.

Once debranched, the whip is taken at 90° to the direction of the travel, to a set of seven saws, where it is cut to six lengths 25 cm long. Just after the whip is cut, six cameras positioned above the conveyer inspect cuttings for straightness and grade them according to their mean diameters. The curved cuttings are rejected and disposed of at the end of the conveyer, while all other, accepted cuttings are graded and placed on the conveyer that takes them to the device that will load cuttings into planting magazines.

The present design concept for the magazines calls for heavy cardboard boxes, of a size that would take approximately 4000 cuttings, sufficient for 1 h of planting in a spacing of 0.3 m between cuttings, at a ground speed of 2.5 km/h, and assuming two boxes per planting head.[1],[2]

Bulk handling of cuttings is considered the most difficult design problem; the device that will transfer cuttings from the conveyer into the planting magazine must deposit each individual cutting in a controlled manner into the box, moving horizontaly and vertically, while depositing layers of cuttings in a uniform, well-controlled spacing and orientation. When the box is full, it will be sealed in a plastic bag, to prevent the loss of moisture during the time it will be stored in the cold storage area, waiting for the planting operation.

MACHINES FOR PLANTING OPERATIONS

Planting of hybrid poplar cuttings is currently done by hand. It is a slow and labour intensive operation; 25-cm-long cuttings are inserted vertically into soil so that the cuttings are flush with the ground. Mechanization of this operation presents difficult design development problems. Much work was done by agricultural engineers in developing agricultural planting and transplanting machines, and a considerable amount of work is being done in development of semi-automatic and automatic planting machines for containerized tree seedlings and bare root seedlings. Containerized operations can be automated, if containers for seedlings are relatively

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[1] Wozniak, B. 1984. Brainstorming Sessions. School of Industrial Design. Carleton University, Ottawa, Ontario. NRCC. Int. Rep. Contr. No. OST83-00231.

[2] Hussey, K., and Doel, R.G. 1985. Magazine filling and handling device for hybrid poplar cuttings. Forest Machinery Co., Dundas, Ontario. NRCC Int. Rep. Contr. No. OSR84-00133.

symmetrical and structurally rigid so that they can be handled with automatic mechanical devices. However, the bare root seedlings are planted by mechanical planters, where seedlings are singularized by hand and placed into a dibble for planting action.

Automatic Planter for Cuttings

Planting of hybrid poplar cuttings presents a difficulty; the cuttings must be singularized, so that they can be planted. The cuttings can be either picked by hand or by a device designed to emulate the work of human hands. Some work was reported on singularization of bare root seedlings (Graham and Rohrbach, 1981; Bowen, 1981); the work was experimental, and no attempt was made to build a commercial prototype planter. Also, design of a semi-automatic planter for cuttings was contracted to a Swedish firm by the International Energy Agency;[1] this machine will be equipped with a platform for an operator, who will feed by hand containers for cuttings.

The Bioenergy Program of the NRCC has developed on contract a prototype automatic planter for hybrid poplar cuttings: (Anon, 1983c).[2-4] The basic planting functions are bulk handling of cuttings, singularization of cuttings, and transfer of cuttings to the device that places them in the soil.

Bulk handling of cuttings proved to be the most difficult design development problem; any induced movement of cuttings in the process of singularization has proven unacceptable during laboratory testing of various containers and devices for the singularization of cuttings. The cuttings tend to bridge, clog, and hang-up, as soon as any relative motion between cuttings and the enclosure is induced into the mechanism. The

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[1]Papadopol, C.S. 1985. Stand Establishment of Fast Growing Species. International Energy Agency, Program Group C. Ontario Ministry of Natural Resources, Maple, Ontario. Int. Report.

[2]Paladino, P. 1982. Feasibility and design concepts for an automatic planter. Timberland Equipment Limited, Woodstock, Ontario. NRCC Int. Rep. Contr. No. OSX81-00120.

[3]Wozniak, B. 1984. Brainstorming Sessions. School of Industrial Design. Carleton University, Ottawa, Ontario. NRCC. Int. Rep. Contr. No. OST83-00231.

[4]Hussey, K., and Doel, R.G. 1985b. Magazine filling and handling device for hybrid poplar cuttings. Forest Machinery Co., Dundas, Ontario. NRCC Int. Rep. Contr. No. OSR84-00133.

decision was made to keep cuttings undisturbed and move the pick-up device to the cutting. The choice of the device was between a mechanical finger-like mechanism, which would be directed to the cutting by a visual recognition camera, and a blind suction type of a device, which would repeat the pick-up operation until a cutting is secured by the suction nozzle of the device. The suction nozzle device was considered less troublesome and less costly then a visual recognition device equipped with finger pick-up mechanism.

A prototype of a single planting head device with suction pick-up was developed by the NRCC. The illustration in Fig. 41 shows singularization, bulk handling arrangement, and transfer of cuttings to the planting conveyer.

Robot pick-up arms are shown in different positions, as they go through the cycle of singularizing cuttings. When a cutting is sensed in the pick-up nozzle, the device is moved into a position where the cutting is oriented vertically, ready to be extended out into the path of the next grab arm for the transfer to the conveyer, which then plants the cutting into the ground. All functions, including the extension into pick-up position, are controlled by a microprocessor. There are eight pick-up arms per box of cuttings, equipped with nozzles. Four arms are positioned on each side of the conveyer track. They are all independently controlled by the microprocessor, so that only one arm extends in front of the oncoming pick-up device on the conveyer.

The conveyer moves in a continuous motion and places cuttings in a slit in the soil, prepared by a heavy coulter wheel in front of the furrow plow shoe, which is hollow to receive the cutting. Soil is then compressed around cuttings by discs and compacting wheels on each side of the furrow.

The magazine, of heavy cardboard, is made so that before it is placed on the planter, the top and the side facing the conveyer are removed, to allow free access to cuttings by the robot arms. The magazine is then moved up, so that cuttings can be picked up. When required it is again moved up to allow for the cuttings already removed. The magazine also moves back and forth, so that cuttings are removed uniformly from the box.

Distance between cuttings is determined by the spacing of the planting hands on the chain; these will normally be adjusted before planting, for any given rotation.

The commercial planting machine should be of a modular design, where planting modules can be adjusted for the width of spacing between rows. The power requirement for a single module is estimated at 15 kW.

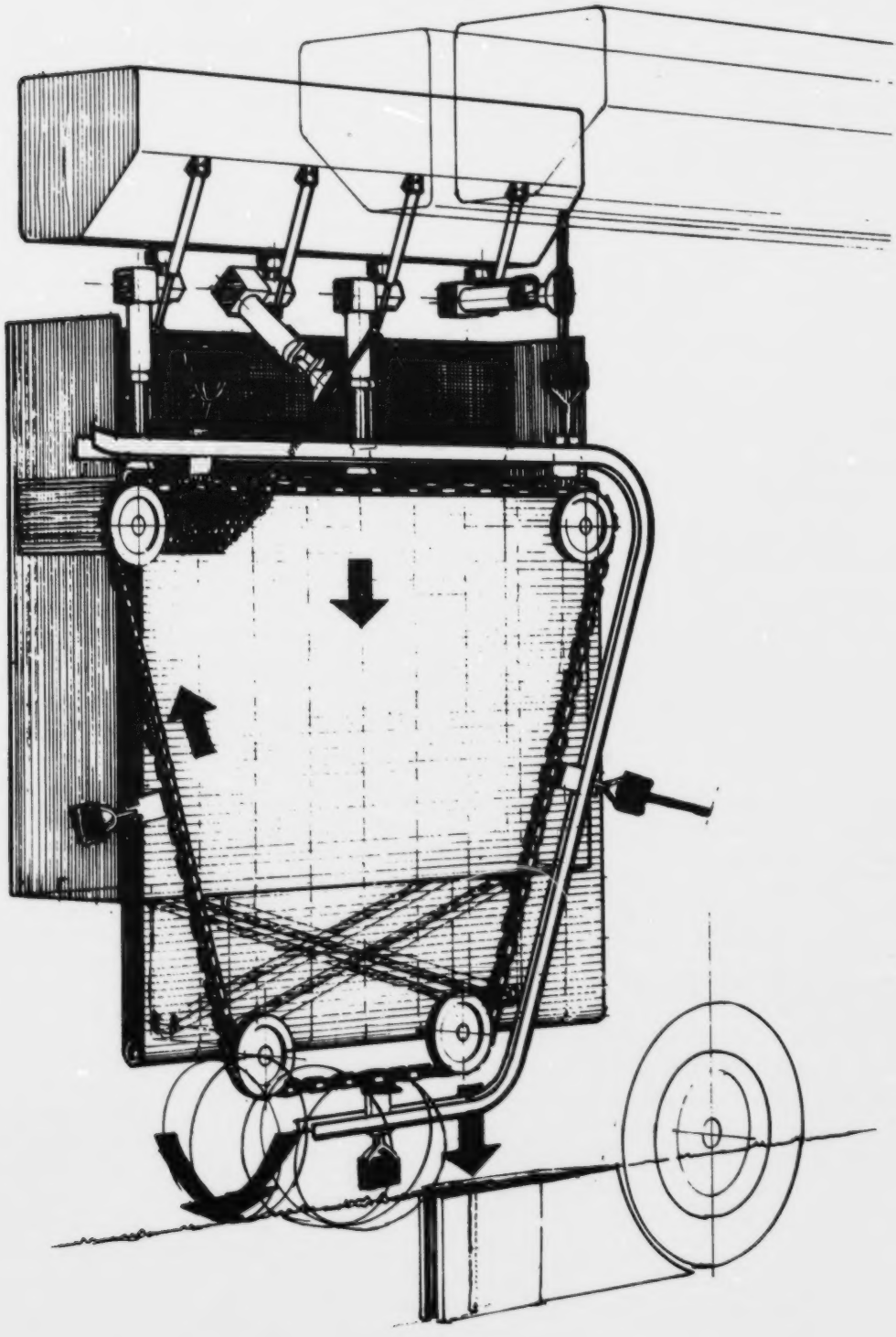

Figure 41. Details of NRCC automatic planter

Transportation Vehicles for Magazines

Planting of cuttings will require support equipment, which will bring new magazines, as those on the planter are emptied. The replacement of magazines requires a special attachment to the farm tractor, to enable the operator to pick up a new magazine from the magazine field wagon and then place it onto the planting machine, in a manner so that the magazine can be engaged into the track on the planter and rolled into planting position.

The operation of loading new magazines on the planter is shown in Fig. 42. The operation illustrated in Fig. 42 shows a 4-row planter. Planting heads will be adjustable for the spacing between the rows, for different rotations; a dense, 2-year rotation plantation, will require 33 333 cuttings per hectare.

A 4-row planter with eight magazines of 4000 cuttings each will need replacement magazines approximately every operating hour.

TENDING MACHINES

Plantation tending operations cover several types of equipment, depending on the kind of cultivation best suited for a particular plantation and soil site. The variety and persistance of weeds govern the decision on whether or not to use mechanical or chemical weed control equipment. Also, the equipment for the application of fertilizers comes under the general scope of plantation tending.

Equipment for Mechanical Cultivation

Between-rows cultivation of 5- and 10-year rotation plantations can be done with agricultural cultivators, modified for the spacing between the rows of trees.

Cultivation of the 1- and 2-year rotation plantations will require machines developed specifically for the narrow spacing between the rows; also, since the growth in the first year is relatively low, the cultivator can straddle several rows, if designed for a sufficient clearance above the 1-year growth of trees.

Equipment for Application of Fertilizers

Fertilizers can be applied either by themselves or in combination with mechanical cultivation; the practice of combined operation is becoming popular in agriculture.

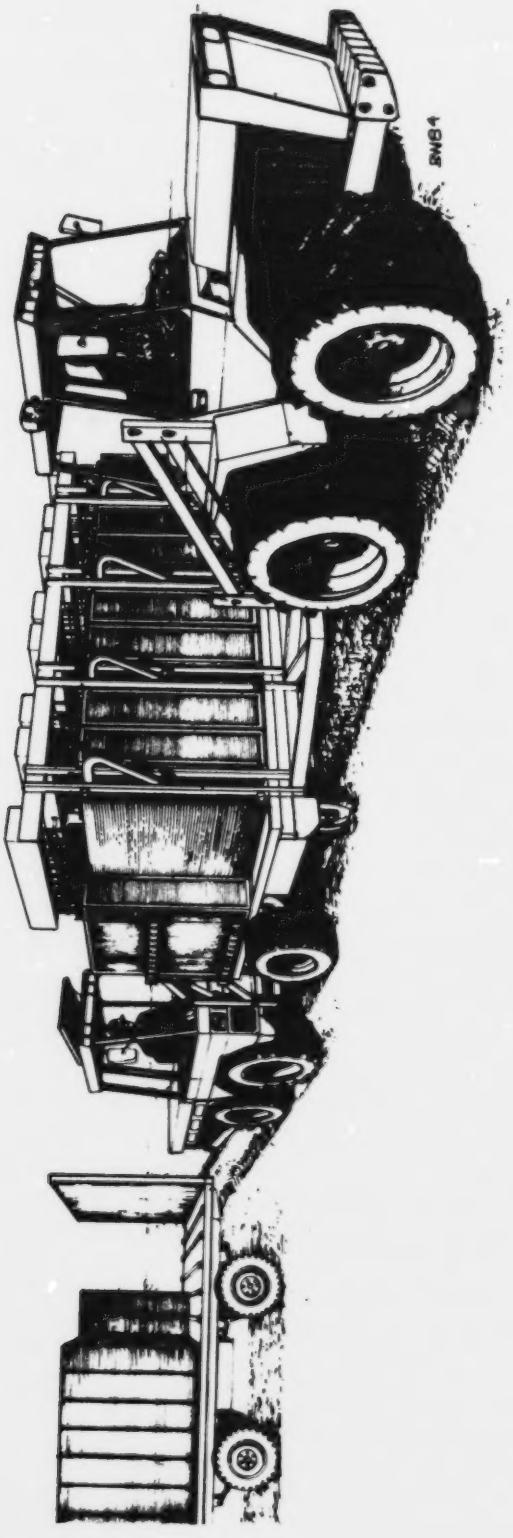

Figure 42. Loading of magazines on planter

The application of fertilizers is either in the liquid form, or granular. Granular fertilizer systems are equipped with pneumatic distribution from the tank to the application nozzles; this system is often used in combination with mechanical cultivation.

An experimental system for application of fertilizers to orchards, uses a narrow band type of a coverage, where a high concentration of fertilizer is applied in a longitudinal strip, over an area of the most dense root systems.[1] This is an experimental approach, which, if successful, will eliminate weeds within the fertilizer band, because of its heavy coverage; area not covered by the fertilizer is cultivated with the cultivator.

Applicators of Chemicals

Chemicals are applied to the plantations with agricultural equipment; however, the spacing between rows may require modified equipment. Also, the equipment for 1- and 2-year rotation will require spraying equipment designed for high clearance above the 1-year growth. This equipment can cover several rows of trees in one pass.

HARVESTING MACHINES

Basic functions of SRF plantation harvesting machines include infeeding mechanisms, severing devices, tree gathering systems, tree accumulators, and off-loading mechanisms. These functions are found in all continuous plantation harvesters.

Relatively little information exists on SRF harvesting machines; some experimental work was done in Sweden, the United States, and Ireland, as well as in Canada (Crafoord et al., 1980; Mattson, 1983; Curtin and Barnett, 1985).[2,3]

A fair amount of information exists on studies of various devices for cutting trees (Wiklund, 1967; Golob, 1976; Golob and Silversides, 1978;

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[1]Hergert, G. 1985. Private communication.

[2]Jones, K.C. 1983. The status of forest energy plantation mechanization. International Energy Agency Report. Swedish Board of Energy Source Development, Stockholm, Sweden.

[3]Golob, T.B. 1982. Mechanization of hybrid poplar energy plantations. Proceedings, The Fourth Bioenergy R&D Seminar, Winnipeg, Manitoba. National Research Council of Canada, Ottawa, Ontario.

1978.[1-3] The choice as to what cutting tool should be used on SRF harvesters was governed by the requirement of a clean cut, without any damage, to provide an acceptable base for the coppice regrowth.

This study divides SRF harvesters into four groups: small dense growth harvester for 1-year rotation whip plantations and the harvester for 2-year rotation hybrid poplar plantations were discussed in the section for the whip harvester; harvesters for 5- and 10-year single tree plantations are, because of tree sizes, different machines. The machine that will harvest 5- and 10-year coppice grown trees is also a different machine, because of a different growth and size of trees.

Small Single Tree Harvester

The Bioenergy Program of the NRCC has developed on contract a prototype harvester for 5-year rotation hybrid poplar plantations (Anon, 1983c.[4],[5] The machine is an attachment for a relatively small, 64 kW tractor. It was designed to harvest hybrid poplar trees of a maximum 20-cm diameter and of a maximum height of 10 m. The average weight of trees was given as 32 kg; however, the maximum weight is about 80 kg per tree, and the actual average weight of trees is more like 27 kg per tree. The spaces between trees and between rows of trees are 1.5 m. The prototype is illustrated in Fig. 43. The infeed mechanism, including the signal device

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[1]Gordon, D., and Voss, D. 1984. Feasibility study for the design of a coppice harvester for hybrid poplar plantations. J.D. Reed Machine Limited, Brantford, Ontario. NRCC Int. Rep. No. OSR84-00080.

[2]Jasinski, S.K., and Robb, D.S. 1984. Development of a harvester for ten year old hybrid poplar plantations; Analysis of requirements. HYD-MECH Forestry Ltd., Woodstock, Ontario. NRCC Int. Rep. Contr. No. OSR84-00078.

[3]Jasinski, S.K., and Robb, D.S. 1984. Development of a harvester for ten year old hybrid poplar plantations; Feasibility study and concepts. HYD-MECH Forestry Ltd., Woodstock, Ontario. NRCC Int. Rep. Contr. No. OSR84-00078.

[4]Gilles, W. 1983. Brainstorming Sessions. School of Industrial Design. Carleton University, Ottawa, Canada. NRCC. Int. Rep. Contr. No. OST83-00231.

[5]Jasinski, S.K., and Whitehead, P.G. 1984. Development of a harvester for five year old hybrid poplar plantations. HYD-MECH Forestry Ltd., Woodstock, Ontario. NRCC Int. Rep. Contr. No's OSX82-00061, OSX83-00039, and OSR84-00154.

Figure 43. NRCC prototype harvester for 5-year rotation plantations

indicating that the tree is being cut, and the severing devices, are illustrated in Fig. 44. The trees are cut by two typical circular, crosscut saws of 61-cm diameters, with a 6-mm thick kerf. The saws have replaceable teeth made of high speed steel, with a 2.5-cm pitch. The saws rotate at 1900 rpm, or at a circumferencial velocity of 61 m/s, which is a sufficient cutting speed for a ground velocity of 2.5 km/h. At a flow of 1.7 dm^3/s, and the system pressure of 17.24 MPa, the maximum power used by the two saws is 29.3 kW. The rest of the harvester's hydraulic system's rate of flow of hydraulic oil is approximately 1 dm^3/s, which, if used at full pressure, would require approximately 17 kW of power. The total available tractor pto power is 52 kW.

The infeed arm shown in Fig. 45 is activated by the signal from the bars above the saws; as the two bars move in when the cutting function begins, the signal initiates the automatic cycle, and the infeed arm swings in, and pushes the tree into the accumulator, shown in Fig. 44. The timing of movements was designed to accomodate 1.5-m spacing between trees and ground speed of 2.5 km/h; the infeed arm must return to its original position before the machine encounters the next tree.

The automatic cycle is controlled through a small, relatively inexpensive, programmable microprocessor; the processor is equipped with four I/O units, each having four input-output points. The programming console is quite small and easy to use. The EPROM memory unit can be erased, corrected, or reprogrammed. The whole unit is mounted in the tractor cab; it takes a few seconds to connect or to disconnect and remove it at the end of the day.

When full the accumulator is emptied by the unloading device, which grabs the ready bunch of trees, pulls it out from the accumulator, and unloads the bunch of trees on the ground. The NRCC prototype unloading device is illustrated in Fig. 45a, showing the bunch of trees dropped parallel to the travel of the machine.

The unloading device in Fig. 45b depicts the device unloading trees at 90° to the travel, as illustrated, also in Fig. 43. The existing harvester was designed to unload bunches parallel to the direction of travel, with the intent to skid trees to the roadside. However, the field trials indicated that the operation could be improved if the bunches were unloaded at 90° to the travel. The operation could prove more productive if a front end piler was used, instead of a skidder; the piler could scoop several bunches of trees in one pass, as illustrated in Fig. 46.

However, if front end pilers were used, the operation of the harvester and pilers would become interdependent, because the bunches would have to be removed before the harvester starts working the next row; otherwise the row of bunches would overlap, which would make their removal difficult.

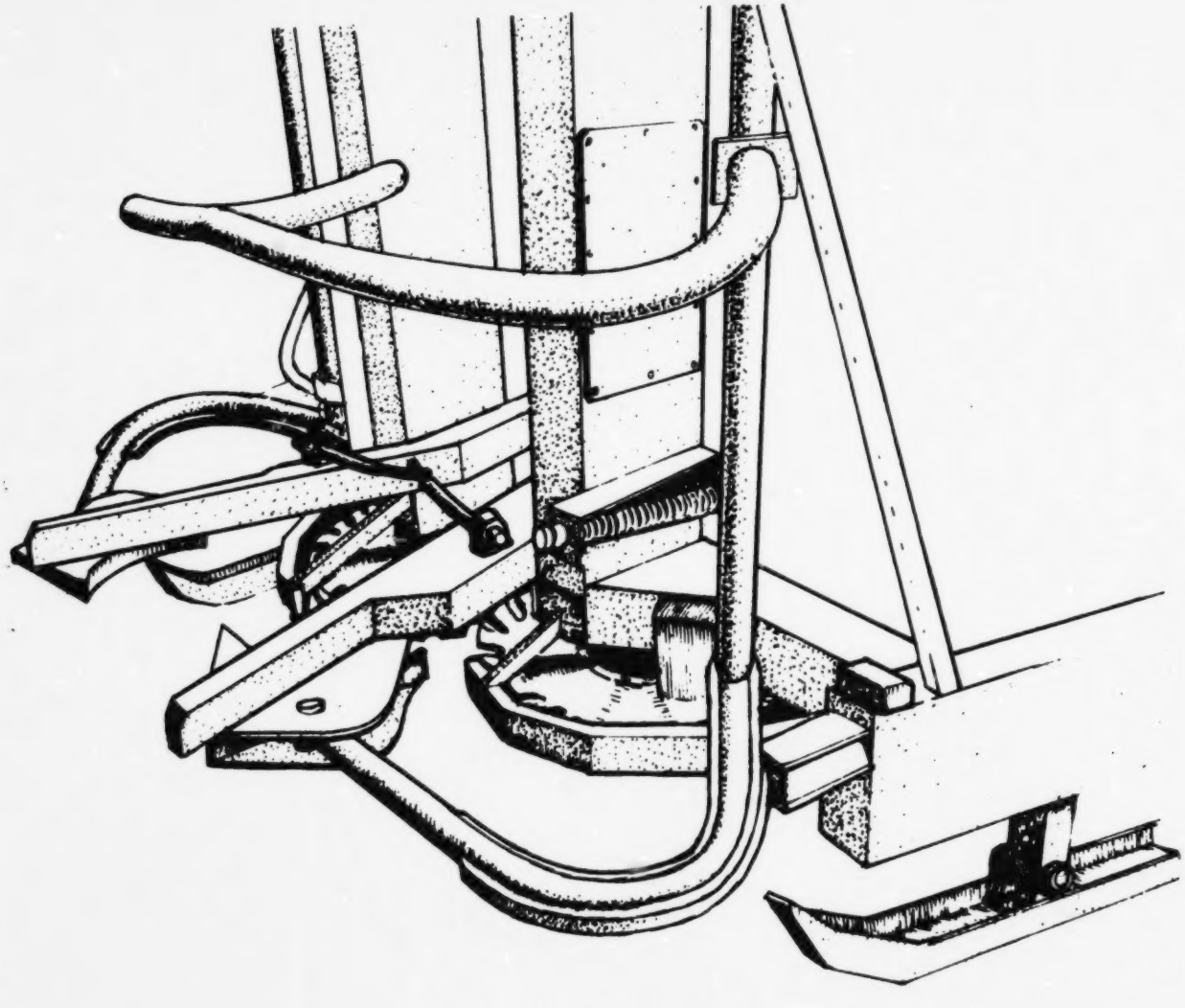

Figure 44. Infeed and severing devices on the 5-year rotation harvester

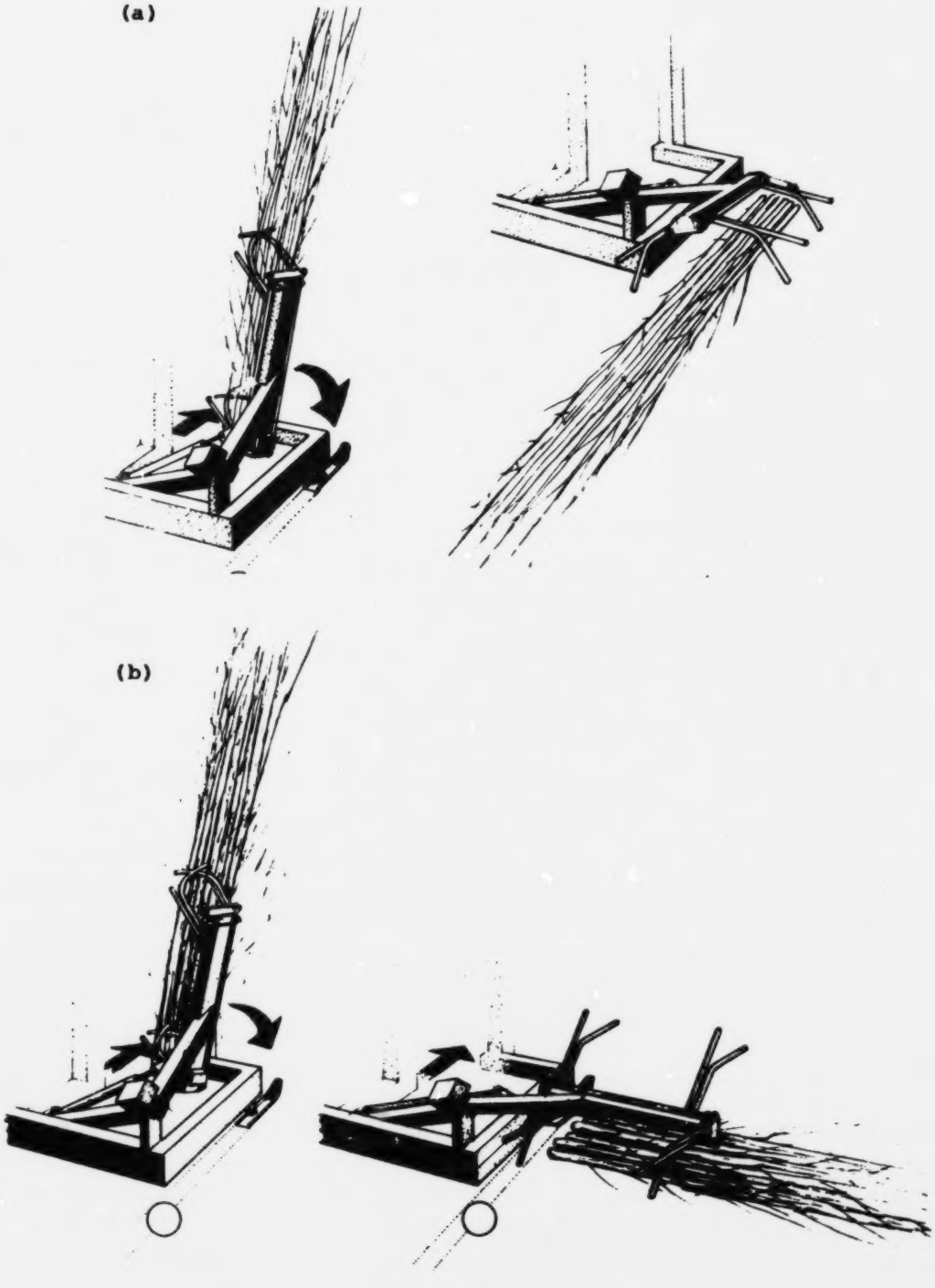

Figure 45. Device (a) for unloading bunches parallel to the travel, device (b) unloading at right angle to the travel

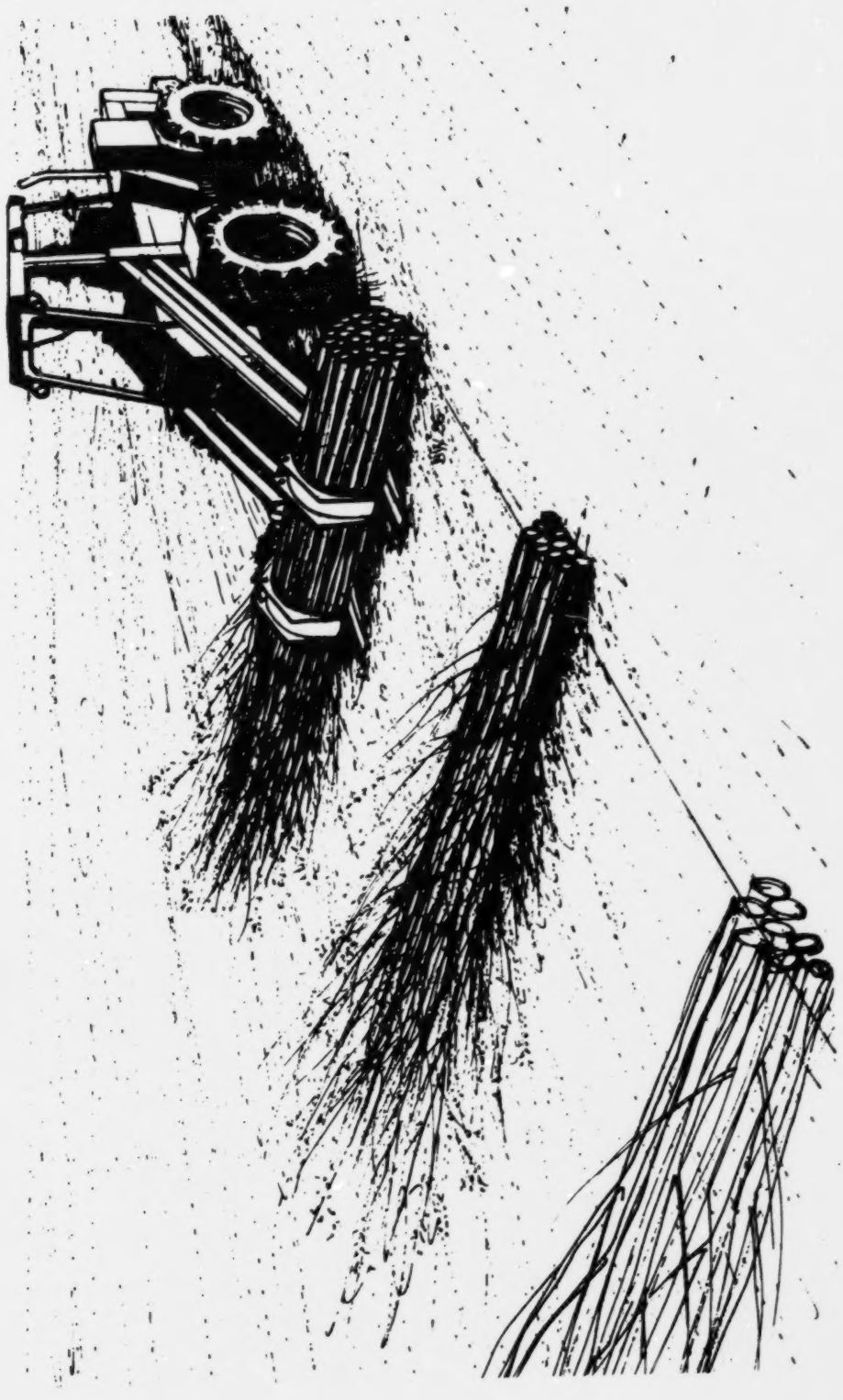

Figure 46. Front end piler gathering bunches of trees

The analysis of cost and productivity pointed out the possible advantages in harvesting two or four rows of trees simultaneously; the cost of harvesting per oven dry tonne is decreased by $4.65, if the plantation is harvested by a 4-row harvester, instead of a single-row machine. Such a 4-row harvester concept is illustrated in Fig. 47.

The basic harvesting functions, infeed, severing, and primary accumulating, are very similar to those of the prototype shown in Fig. 43, except for modified primary accumulators, of which there are only two, one per side, with two cutting devices on each side, feeding accumulators positioned on each side of the harvester. A major difference between the prototype and the 4-row harvester in Fig. 47 is in two horizontal accumulators, one per side, which are loaded by two independent devices, that take trees from the primary, vertical accumulators and deposit them onto the horizontal accumulators. These main, horizontal accumulators are unloaded by tilting them to the rear of the machine and sliding the bunches of trees onto the ground. The concept of a 4-row machine is possibly the optimum approach under present economic conditions.

Large Single Tree Harvesters

Design criteria for 10-year rotation hybrid poplar plantations were established as: average tree stump diameter is 25 cm, average tree height is 15 m, average tree weight is 136 kg, spacings between trees and between rows are 3 m. A prototype was developed by the Bioenergy Program of the NRCC on contract (Anon, 1983c).[1-3] The prototype is very similar to the 5-year rotation plantation harvester shown in Fig. 43; however, the 10-year rotation harvester is a much larger machine. The main difference is in the cutting device, the 10-year rotation harvester is equipped with a single circular saw of 137-cm diameter and a tooth pitch of 38 mm. The saw has a 48-mm thick kerf, and operates at 1240 rpm. It is run by a hydraulic oil flow of 3.1 dm^3/s, at a maximum pressure of 17.24 MPa. It requires 53 kW

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[1]Wozniak, B. 1984. Brainstorming Sessions. School of Industrial Design. Carleton University, Ottawa, Ontario. NRCC. Int. Rep. Contr. No. OST83-00231.

[2]Jasinski, S.K., and Robb, D.S. 1984. Development of a harvester for ten year old hybrid poplar plantations; Analysis of requirements. HYD-MECH Forestry Ltd., Woodstock, Ontario. NRCC Int. Rep. Contr. No. OSR84-00078-

[3]Jasinski, S.K., and Robb, D.S. 1984. Development of a harvester for ten year old hybrid poplar plantations; Feasibility study and concepts. HYD-MECH Forestry Ltd., Woodstock, Ontario. NRCC Int. Rep. Contr. No. OSR84-00078.

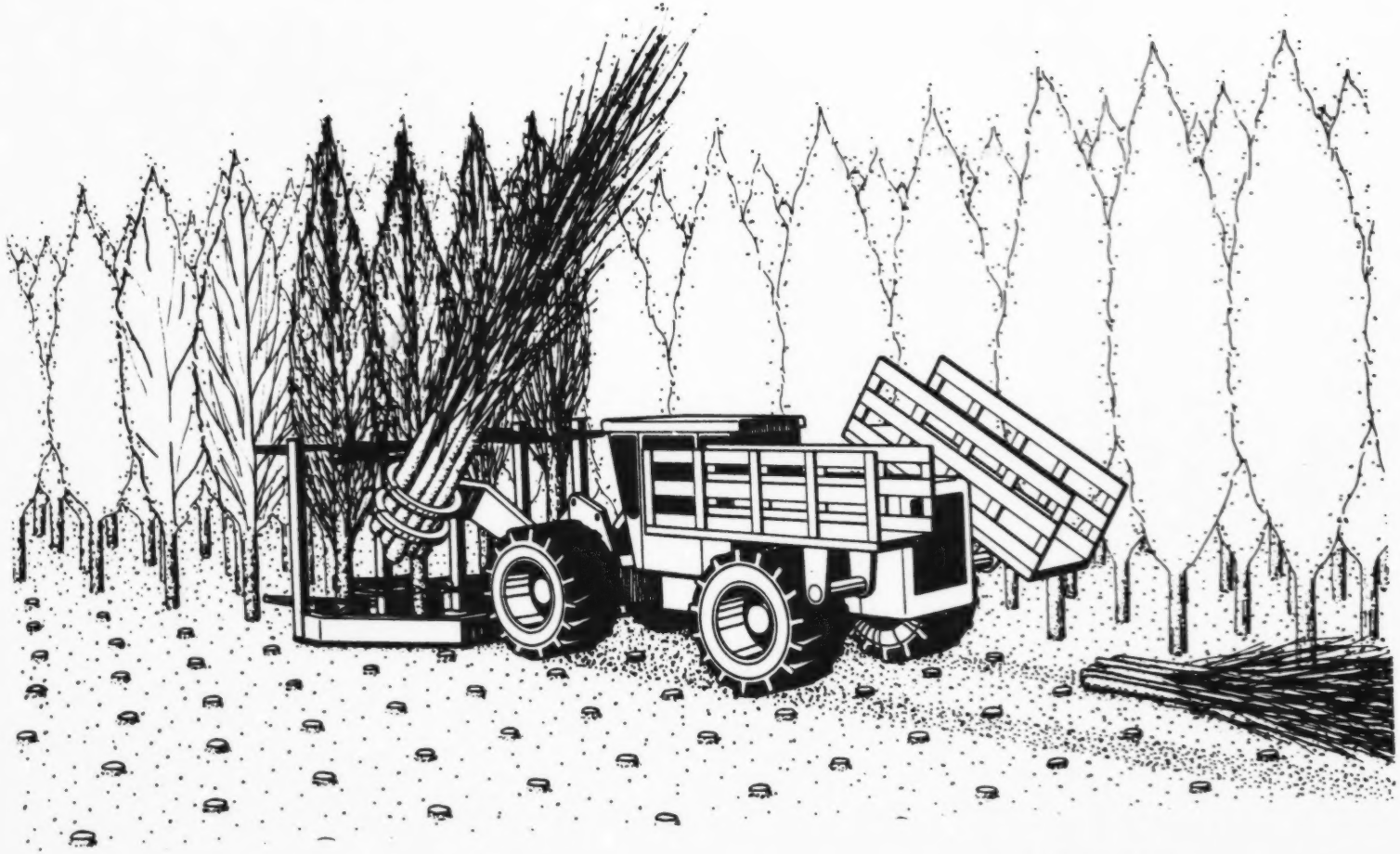

Figure 47. Concept of a 4-row harvester for 5-year rotation plantations

of power, and it rotates at a circumferencial velocity of 89 m/s. The saw was manufactured from a 690 MPa high strength steel, heat treated after the machining operations had been completed.

The weight and the size of the saw act as a flywheel. It stores energy when cutting small trees or when not cutting; this energy is then used when severing a large diameter tree.

The prototype has two accumulators, like the prototype in Fig. 43, only, the accumulators are much larger then those on the 5-year rotation machine. Bunches of trees are off-loaded to the clear cut side, parallel to the direction of travel, as illustrated in Fig. 45a.

The prototype is attached to a large off-road tractor, equipped with a 130 kW engine.

An oil flow of 2.84 dm^3/s is available for other power functions. At a pressure of 17.24 MPa, the system will develop an additional 49 kW of power.

The automatic control system is the same as the one described under the 5-year rotation harvester.

The cost and productivity analysis of the 10-year rotation plantation harvesting indicates that a saving of $1.81/ODt can be achieved by harvesting the trees with a 2-row harvester. A concept of the 2-row harvester is illustrated in Fig. 48, showing two saws, two vertical accumulators, and transfer devices taking bunches of trees from the vertical accumulators and depositing them onto the horizontal accumulators; from there bunches are rolled off and dropped to the ground.

This machine would double the production, but it is considerably more expensive to build. Because of a rather high power requirement, the machine may need an auxiliary power plant to supplement the power on the carrier tractor, assuming that the same tractor is used for the 2-row harvester, shown in Fig. 48, as the one used for the existing prototype.

Small Dense Growth Harvester

As mentioned beforehand, the small, dense growth harvester was discussed under Whip Harvesting Machines. The 2-year rotation coppice growth is considerably taller and thicker then the 1-year growth of whips; however, the machine designed to harvest 2-year coppice growth can be used to harvest whips.

The band saw severing device is equipped with a modified crosscut band saw, with deeper gullets, and the saw teeth bent to make a thicker kerf;

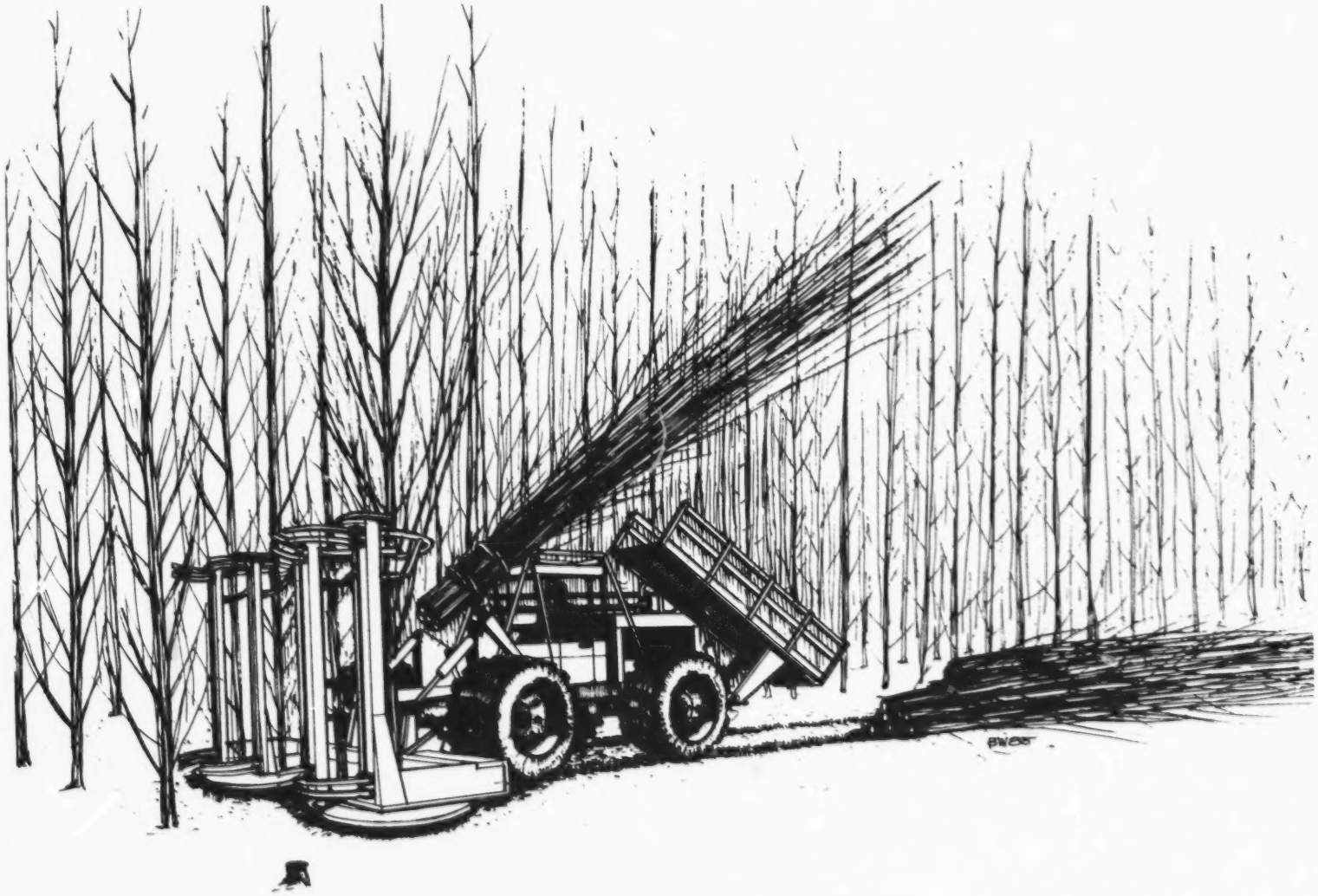

Figure 48. Concept of a 2-row harvester for 10-year rotation plantations

the teeth have a pitch of 19 mm. The prototype harvester shown in Fig. 38 was designed to harvest 1- and 2-year coppice grown hybrid poplar plantations. The NRCC prototype deposits bundles of stems to the ground; bundles can be collected by a tractor equipped with a hydraulic loader and loaded onto a field trailer, which is taken to roadside, where the loader unloads and piles bundles for drying and eventual chipping.

A large front end piler could be used as an alternative method to gather and forward bundles to the roadside; such a front end piler would collect and take to the roadside several bundles of stems at a time.

A relatively low biological productivity per hectare per harvest of a 2-year rotation plantation makes for a high harvesting cost per oven dry tonne, compared to the cost per ODt of 5- and 10-year rotation plantations, with considerably higher yields per hectare. A 4-row harvester would improve the cost per oven dry tonne of a 2-year rotation plantation. Unloading of bundles in a 4-row harvester could present difficulties; however, the unloading could be done in a manner similar to that of the 4-row harvester for 5-year rotation plantations shown in Fig. 47, with a possible modification to the mechanism for transfer of bundles from vertical to the horizontal accumulator. The transfer of bundles may require a continuous chain type conveyer, because of the continuous infeeding of densely grown biomass.

Large Growth Coppice Harvester

The subsequent harvests of 5- and 10-year rotation hybrid poplar plantations require harvesting equipment capable of severing and handling several stems from the same stump; the stems are not necessarily straight within the height of the harvester infeed mechanism.

A coppice harvester is illustrated in Fig. 49. This prototype was developed by the NRCC on contract.[1],[2] The cutting device on this harvester is a prototype reciprocating saw, designed to reciprocate at 800 cpm, with a 250-mm stroke. The total hydraulic flow of 1.89 dm^3/s is supplied by a

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[1]Wozniak, B. 1984. Brainstorming Sessions. School of Industrial Design. Carleton University, Ottawa, Ontario. NRCC. Int. Rep. Contr. No. OST83-00231.

[2]Gordon, D., and Voss, D. 1984. Feasibility study for the design of a coppice harvester for hybrid poplar plantations. J.D. Reed Machine Limited, Brantford, Ontario. NRCC Int. Rep. No. OSR84-00080.

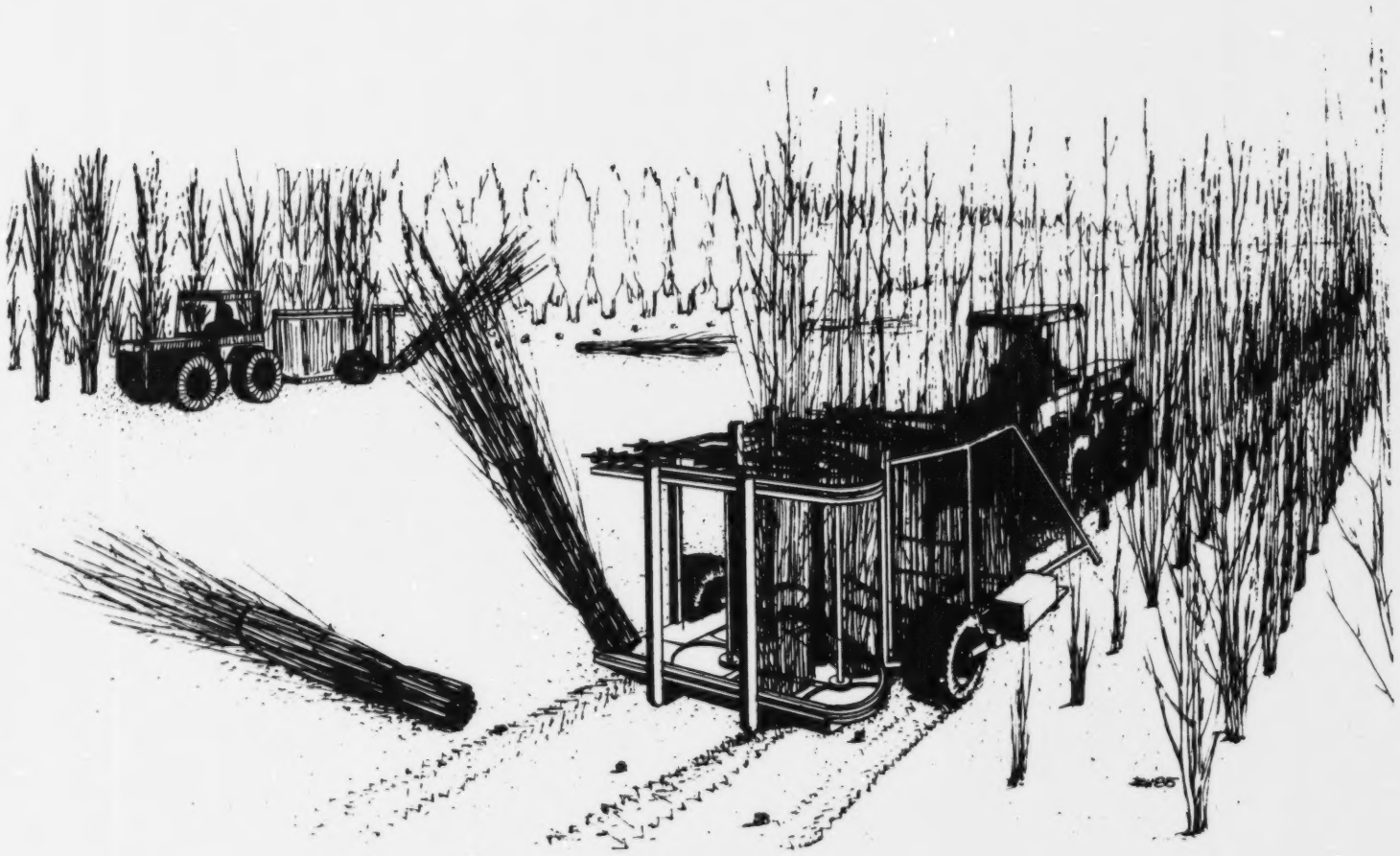

Figure 49. Coppice harvester for large coppice growth

pto mounted gear pump, with a priority divider to the saw mechanism.[1] The device is pivoted on the tractor end of the mechanism, so that the the cutting end freely swings back under varying cutting loads, and at the reversal of the stroke. The pivot is controlled by a spring loaded device.

The blade pitch configuration is illustrated in Fig. 50a. The experimental blade thickness, or the total kerf thickness, is 2.7 mm. This device severed 15- to 18-cm diameter trees, cleanly and with no difficulties. Power curve for the experimental device is shown in Fig. 50b, indicating a relatively low cutting power demand, at motor speeds between 500 and 600 rpm.

Tests in smaller stems were conducted at a motor speed of 1300 rpm; power requirement during cutting was 3.4 kW, where the actual cutting power requiremnt was only 0.9 kW.

This experimental saw with smaller pitch was proved capable of cutting stems of 2 to 10 cm in diameter, without saw swingback to increase the available cutting time.

The disadvantage of the present cutting device is its large gearbox. A possible reduction in the size of the gearbox was studied, and it was determined that the box could be reduced in size by 50% in volume by using a somewhat shorter stroke and minimizing the mass of the reciprocating components.

The cutting device is subject to a fairly pronounced vibration, caused by the torsional moments exitation of the saw blade. The vibration can be reduced considerably by introducing another set of counterweights at right angles to the primary set; this approach would increase the size of the transmission box, and it could be justified only with the use of a double row severing device, where the additional counterbalance would be located between the two rows of trees. In the case of a 4-row harvester, each side of the machine would be a unit with its own additional counterbalance at right angles to the counterweights, which are acting in line with the saw blades.

The infeed system on the coppice prototype was made of a 10-cm pitch conveyer chain, with the addition of special lugs to facilitate the infeed and elevation of stems. During the initial field trials, the conveyer was out of step with the ground speed, causing jamming and clogging of the

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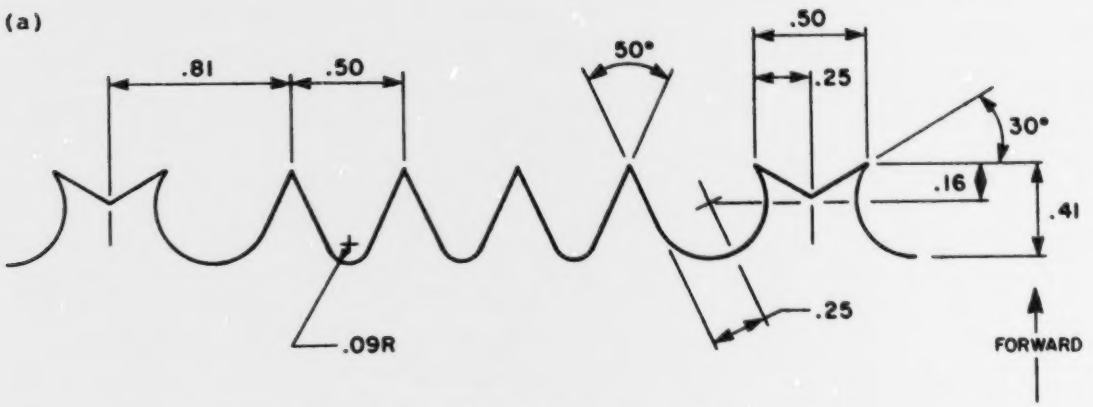
[1]Gordon, D., and Voss, D. 1984. Feasibility study for the design of a coppice harvester for hybrid poplar plantations. J.D. Reed Machine Limited, Brantford, Ontario. NRCC Int. Rep. No. OSR84-00080.

(a)



— FOUR CUTTING ELEMENTS FOLLOWED BY DRAG LINK
— TOOTH BEVEL ANGLE 30°
— KERF .015 FROM SURFACE OF BLADE ALTERNATES ON CUTTING ELEMENTS ONLY
— FLAME HARDENED AND TEMPERED TO Rc 45-50
— DRAG LINK TIPS SLIGHTLY RELIEVED FROM CUTTING TEETH TIPS

(b)

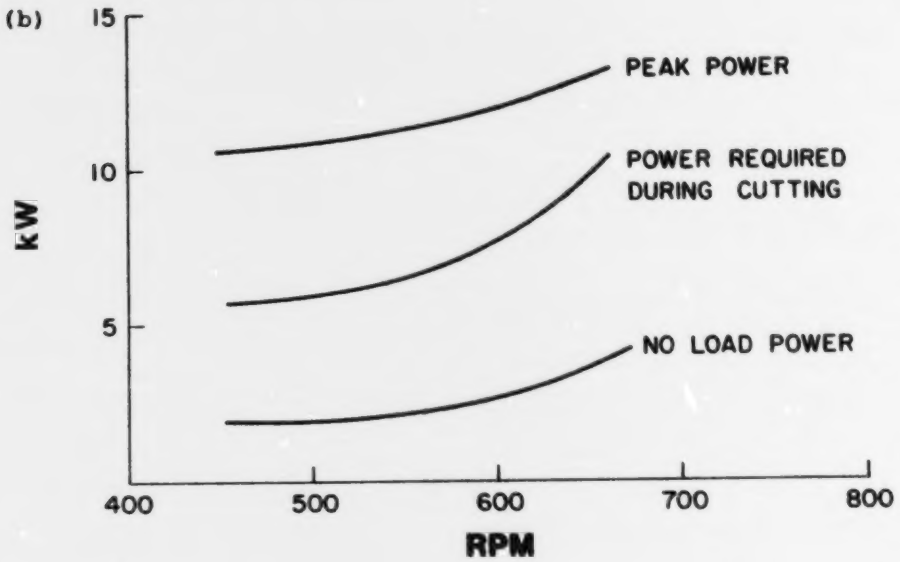


Figure 50. (a) Saw pitch configuration; (b) Power requirements (reproduced from Gordon, D., and Voss, D. 1984. Feasibility study for the design of a coppice harvester for hybrid poplar plantations. J.D. Reed Machine Limited, Brantford, Ontario. NRCC Int. Rep. No. OSR84-00080)

conveyer. When the ground speed was timed with the infeed speed, the infeed system worked well. The prototype has been modified to maintain a controlled, fixed ratio between the infeed conveyer speed and the vehicle ground speed.

The gathering and accumulating mechanisms consist of a system of linkages running off a crankshaft on the main power shaft for the conveyer chain. The gathering linkage resembles the device on the 2-year rotation plantation harvester.

Bundling and tying of bunches of stems is done by an agricultural knotting device, modified for the size and shape of bundles. Since the average size of harvested material has not been fully established, the bundling device may prove to be of insufficient strength, for the size of coppiced stems. The final decision on bundling of the harvested material will be made when more is known about the growth of the 5-year rotation hybrid poplar. If the growth is large enough, the bundling and tying of stems may not be required.

The 10-year, coppice-grown hybrid poplar trees are large enough to be treated as individual trees, especially because the available information indicates that only a single stem per stump remains after 10 years of growth. Based on the above reports, the 10-year rotation coppice grown hybrid poplar can be harvested with the machine developed for the single large tree harvesting.

CHIPPING EQUIPMENT

Equipment to chip trees is available commercially. This analysis deals only with highly mobile roadside chipping systems, which can be moved quickly from plantation site to plantation site, within the established radius of operations in a particular operational system. A typical roadside chipping system is illustrated in Fig. 51.

The equipment consists of a mobile chipper with a pulling vehicle, or a self-propelled machine of a required power which normally reflects the processing capability of the machine. In this analysis is assumed an operation consisting of a self-propelled chipper, with a gross power of 485 kW, and with a theoretical productivity of 100 t/h.

Feeding and moving of trailers is done by a 63 kW tractor, equipped with a loader and a fifth wheel on the rear frame.

Spare trailers at the roadside landing are included in the transportation equipment. The number of spare trailers depends on chipping capacity, as well as on the capacity of the transportation system.

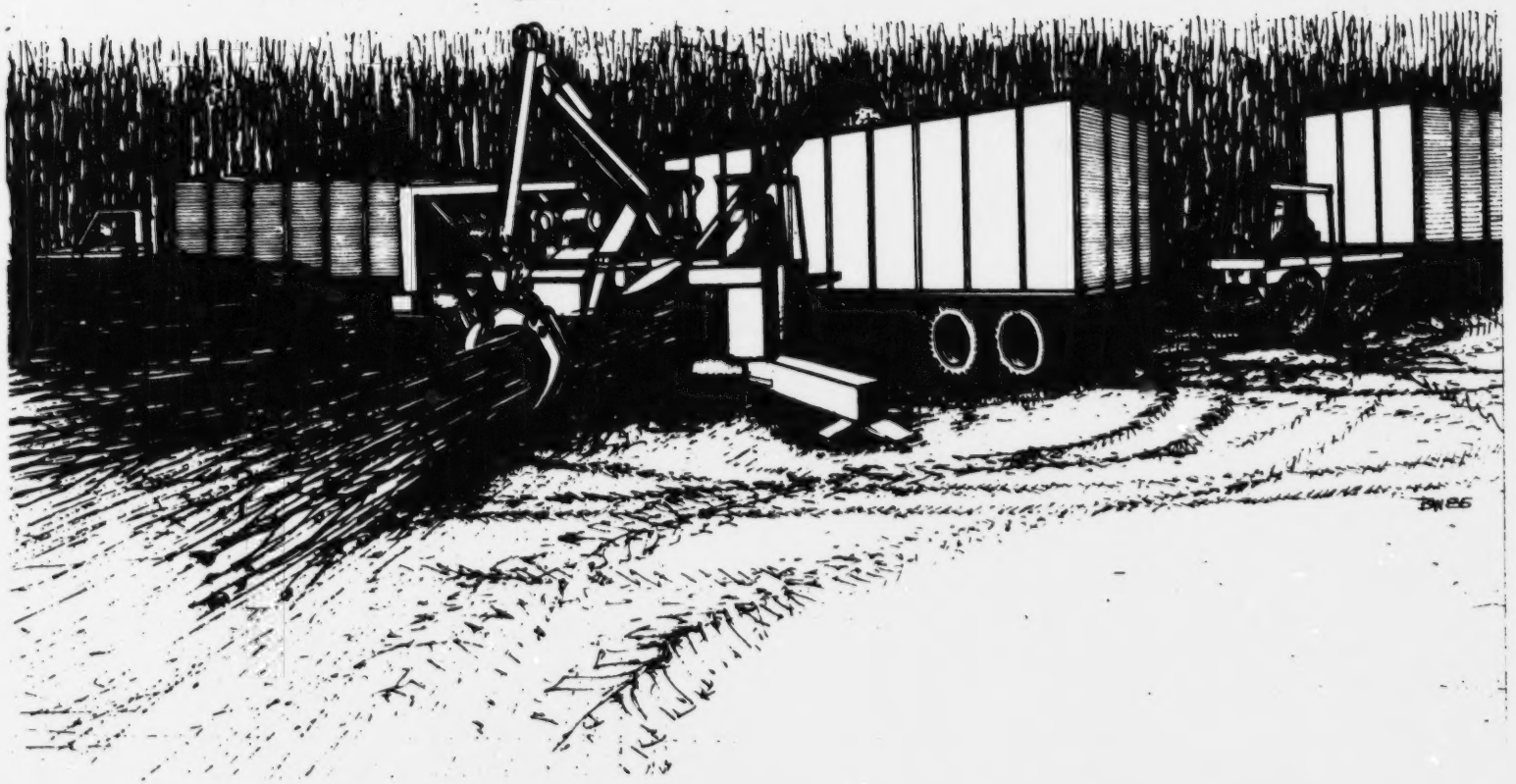


Figure 51. Roadside landing biomass chipping system

Figure 52. A typical unloading system at the plant

Chipping and transportation systems should be designed for a given road system, accessibility of the plantation, and the size of the plantation site.

Transportation Equipment

The wood chip transportation system is a link between the last operation at the plantation site and the processing destination point. The system must be optimized for a desired chipping system, to achieve minimum delays at the roadside chipping operation. The spare trailers at the chipping site are considered a part of the transportation operation; the number of spare trailers is determined by the distance to the processing plant and the processing capability of the chipping system.

The size of trailers depends on the road system and on the access to the plantation. In this analysis the conditions were assumed satisfactory for the operation of 14-m-long and 4.15-m-high trailers. The overall width of trailers is 2.60 m, which is standard for the Ontario provincial regulations. The load per vehicle per trip was estimated at 32 green tonnes of wood chips. The power required to pull the above chip trailers, is estimated at 260 kW, which calls for a large and heavy truck. As in the case of trailers, the capability of the total system will determine the size of trucks.

At the receiving point, unloading of the trailers should be done by using some kind of a mechanized lifting system, like the system illustrated in Fig. 52, showing a relatively small overhead lift for the trailer. Some lifting systems are quite large, designed to lift truck and trailer, to reduce the waiting time at the processing point.

CONCLUSIONS

This study is an attempt to provide an analysis of all short rotation forestry operations, within the limits of the available information, time, and knowledge. The writer hopes that the study provided a basis for discussions on many interactive problems, concepts, and requirements.

The most important general facts which should be stated are that an organized approach to growing SRF plantations will provide biomass for energy and fibre applications for 5- and 10-year rotations. The final cost of SRF biomass makes it competitive with the market price paid by pulp mills for wood chips and competitive with fuel oil and natural gas in combustion plants.

The Bioenergy Program of the National Research Council of Canada has, during its short existence, provided leadership in systematic research and development of mechanical systems required to mechanize SRF plantation operations. The work was primarily of a mechanical and industrial engineering nature, with necessary inputs of biological and economic factors. A concentrated approach to a sound industrial design played a major role in the development of several harvesting, planting, and other machine concepts. Almost all machine concepts studied and prototypes actually built are of a novel nature, based on automated functions controlled by microprocessors. The data obtained from field trials of conceptual mechanisms have been integrated into a simulation of a proposed total SRF system by means of a computer model which allows a measure of the sensitivity of the final cost to the design assumptions made in the study.

The review of SRF operations points out the importance of a systematic approach to the design of operations, including such operational factors as the layout of plantations. Factors affecting the layout are the size of the plantation site, the length and width of the plantation, and its access to good road systems. It is important to provide as long machine runs as possible for all plantation based operations; long rows of trees minimize the effect of delays in turns on machine productivity. Spacings between trees and between rows are as important for machine productivity as they are for biological productivity of the plantation.

Plantation sites should be free of stones and other debris; also, sites should be as level as possible, free of depressions and hummocks, so that ground speeds of operations are optimized. These requirements can be achieved through a thorough land preparation operation and by subsequent tending and clean-up operations, which will eventually make plantation sites look like typical agricultural land resources.

Typical manual operations, such as those in the nursery, planting, tending, and harvesting, should be fully mechanized, to obtain operational costs that will provide an alternate, competitive source of biomass for energy and other potential uses, such as wood chips for pulp mills. At today's price of wood chips of $49.00/ODt delivered to the mill, the cost of wood chips from SRF plantations, calculated at $30.00 to $35.00 per oven dry tonne, would compete well on the open market. In the case of direct combustion, taking a conservative figure of 2.5 barrels of oil as having an equivalent heating value as 1 ODt of wood chips, and taking 2.5 barrels of oil as equivalent to 397 L of heating oil at $0.35/L for industrial users, and $0.45/L for home users, we have a value of $138.95 to $178.65 for oil, equivalent to the cost of 1 ODt at about $32.00.

The computed costs per hour and per oven dry tonne of wood are in most cases conservative, although some inputs may appear low; however, the composite estimates of all inputs are likely very close to reality. All inputs and computed costs are in 1985 Canadian dollars, with real borrowing rates of 7% and 10% per year. An additional 10% added to the computed costs would likely provide a sufficient amount for the profit and for the possible future inflation.

Mechanical productivity was computed with inputs based on NRCC field tests of prototype machines. A ground speed of 2.5 km/h is considered well within limits of prototypes; also, a delay per turn of 35 s is an approximate average for delays due to turns at the end of rows.

The biological productivity was obtained by interpreting and interpolating recorded and expected productivity of SRF hybrid poplar plantations. The interpretation of reported yields may not be acceptable to some researchers; however, costs per oven dry tonne of wood are computed for given yields and can be adjusted by the percent difference between the given yields per hectare and the desired corrected yield per hectare.

Prototype machines developed by the NRCC have provided a basic understanding of difficulties associated with a new field of industrial endeavour. The prototypes are all single-row machines, designed to prove new mechanisms, and to provide concepts of devices required to execute tasks in row working of forests plantations. The analysis of costs provided information for optimization of operations, by the indication of optimum combination of machine productivity, applied to a known biological productivity per hectare. Concepts of multi-row operations were given as a result of the final analysis; the conceptual drawings of these multi-row planters and harvesters are based on the designs of devices tested by the NRCC as single row prototypes. Any future development of these machines should reflect the experiences gained during the field tests of protoypes.

The accumulated knowledge could provide the background for new industrial developments in areas of machine manufacturing, farming, contracting, and distribution. This industrial development would provide a needed diversification of depressed agricultural regions.

The Bioenergy Program of the National Research Council of Canada, during its existence from 1982 to 1985, has provided leadership in the mechanization of short rotation forest plantation operations. The task was not completed; several more years of development are needed to produce commercially viable machines for SRF operations. The development work done by the NRCC has provided new insights into the mechanization of forest operations. Devices and tools developed will be eventually applied to other then SRF machines, in agriculture and forestry.

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